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Characterization of the Precision Laser Beam Welding Process for the MC4368A Neutron Generator

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Characterization of the Precision Laser Beam Welding Process for the MC4368A Neutron Generator

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Abstract

The design of experiments (DOEx) approach was used to characterize the Precision Laser Beam Welding Process with respect to four processing factors: Angle of Attack, Volts, Pulse Length, and Focus. The experiment was performed with Lap Joints, Nickel-Wire Joints, and Kovar-Wire Joints. The laser welding process and these types of welds are used in the manufacture of MC4368A Neutron Generators. For each weld type an individual optimal condition and operating window was identified. The widths of the operating windows that were identified by experimentation indicate that the laser weld process is very robust. This is highly desirable because it means that the quality of the resulting welds is not sensitive to the exact values of the processing factors within the operating windows. Statistical process control techniques can be used to ensure that the processing factors stay well within the operating window.

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Introduction

From the start of neutron generator manufacturing, resistance welding has been the main joining process used for the power supply assembly. Resistance welding has proven to be a dependable process to use until now. However, it has had inherent limitations, such as the need to have access to both sides of the joint and the lack of true visual or other non-destructive inspection techniques of the weld.

As the power supply design evolved over the years, space and access limitations became more restrictive, making it increasingly difficult to continue using resistance welding to join the power supply components. Concurrently, laser welding moved from the research laboratory to the production floor. In fact, laser welding became widely used in the manufacturing cycle of the neutron tube and other weapons components. With laser welding offering robust design and manufacturing advantages in neutron generator production, the latest neutron generator power supplies are being designed exclusively for laser welding. The MC4531 is the first of these designs. It was intended that once this generator power supply was put into production a re-design of the MC4368 would take place. However, the situation changed, and with the introduction of the MC4368A the joint designs needed prompt modification as the new power supply will be used in the new generator.

The Laser Weld experiment described below was initiated to characterize the laser weld process and to determine the best set(s) of laser weld processing factors, weld schedules (processing parameters) for the various joints on the power supply assembly. The experiment studied the effect of four different processing factors on weld strength and appearance. The four different processing factors were Angle of Attack, Volts, Pulse Length, and Focus. Prior experimentation had indicated that these process factors were the most critical. The Angle of Attack refers to the actual processing angle that is determined by hard, rigid weld fixtures. The fixturing devices that locate generator components determine the angles (line of sight). The fixturing has been designed to compensate for the line of site factor and to optimize attack angles, keeping them as shallow as possible. The greater the weld angle the greater is the chance of producing an unacceptable weld. The primary concern with steep processing angles is an effect known as undercut which could create stress risers or a weakened joint that could lead to failure. The Voltage influences the height of the laser pulse and consequently the depth of the weld penetration or molten weld pool. The Pulse Length refers to the duration of the laser pulse. This processing factor primarily affects the depth of the weld penetration and to a smaller extent the diameter of the weld spot. The Focus setting primarily changes the diameter of the focal spot. The smaller the spot, the more localized the heat input.

The experimental matrix used is given on page A1 of Appendix A. The baseline operating levels used in the experiment were determined from development activities. The design is a Central Composite Design (see Box and Draper (1987)), with three levels for each factor. The experiment was performed for Lap welds (Kovar sheet to Kovar sheet), Nickel-Wire welds (Nickel wire to Kovar sheet), and Kovar-Wire welds (Kovar wire to Kovar sheet). Lap welds make up a very common weld geometry that facilitates an autogenous weld type. An autogenous weld is one that is generated without the use of a filler material (the surfaces being welded together must have intimate contact) and is produced by first melting away or creating a molten puddle and then fusing one or more of the materials being joined. With regards to this process (lap weld, sheet stock) the laser is aimed at the top edge of the upper piece part, creating a concentric spot-weld with a resultant nice shaped fillet. The same holds true for the wire to sheet welds. The only variation is in the round wire geometry that creates a different focal/cross hair alignment point during welding operations. The sheet-to-sheet and wire-to-sheet weld geometries are pictured on page A2 of Appendix A. Photographs of the type of welds made in this experiment appear on pages B2-B8 of Appendix B.

Each combination in the matrix was run twice with Lap Joints and Kovar-Wire Joints and once with Nickel-Wire Joints. The response variables measured were Breaking Strength of the weld (lbs.) and visual Rating (1-5, with 5 the highest rating) of the quality of the weld. The goal of the design of experiment (DOEx) was to identify optimum settings and develop operating windows for the processing factors so that these response variables would be maximized. There is no formal strength criteria to adhere to so the rule of thumb followed is that after a weld is produced it must fail in the wire (base material) and not in the weld fusion zone. A further goal of the experiment was to establish a baseline with regards to weld schedules and to fully characterize both the laser welding process and the A-B Laser system located in Building 870's neutron generator production facility. A final objective was to establish a single weld schedule (if possible) that would encompass all of the eight weld joints on the MC4368 NGSA. Our expectations were that the experimental data would be used to establish an operating window that would take into account all of the processing constraints/variables. The results regarding the operating condition chosen for production and the operating window for each factor will be inserted into the appropriate Work Instruction (WI). It will be available for examination by the operators on the floor and will illustrate the comprehensive range of acceptable weld schedules.

Experimental Procedure

To ensure that meaningful data would be obtained, consistent experimental procedures were carefully developed. The weld sample coupons were identical to War Reserve (WR) coupons certified during early resistance welding on the MC4368 program. Weld coupons varied in thickness, material type, and geometry in order to simulate actual WR piece parts.

Factor levels that appear in the test matrix (page A1) were determined with preliminary experiments such as the "bead on plate" experiment, which is essentially 0 degree processing angle (flat). These experiments were merely to verify that optical focus indeed was an important factor. No actual joints were generated at this processing angle. Initial tests were begun with angles ranging from 17 to 60 degrees on Lap Joint welds. The sample coupons (Kovar sheet stock .010"& .030") were attached to the variable sine bar used to verify the correct processing angles prior to each test. This sequence covered the entire weld schedule spectrum consisting of 5 different weld schedules. The next step in the DOEx was gap experimentation in which a gap was purposely introduced into the weld joint to determine upper limits of processing capabilities. Gap thickness ranged from .003" to .005". The gap experiment included each level of attack angle and weld processing conditions. During actual processing the angle of attack is determined by assembly fixtures and system hardware constraints. As mentioned above regarding varying part geometry, a requirement is to join a .021" diameter wire. The wire is processed in a lap joint configuration fusing the wire to the sheet stock at the tangent point of the wire. The wire to sheet stock experiment incorporated the complete range of processing angles and varying weld conditions. Multiple samples were generated in order to document results of each test by performing mechanical testing, metallography and macro-photography.

I. Equipment

Precision laser spot welding using A-B Laser model STARWELD PERFORMANCE (see picture on page A3).
50-Watt Pulsed Nd: YAG Laser
Pulse Energy up to 80 Joules
Pulse Power up to 8.5 kW
Fixed Optics with 120mm Focal Lens
Sweet Spot Resonator
Pulse Shaping
Motorized Variable Spot Size Adjustment from 0.2-2.5mm

II. Fixtures

Adjustable sine bar/plate for varying weld angles 0 to 90 degrees
Catalog No. 183-6581 RALMIKES TOOL-A-RAMA

III. Weld Coupons

.010” thick Kovar Sheet .380” x 1.00”
.030” thick Kovar Sheet .320” x 1.00”
Nickel 210 wire .021” Diameter
Kovar wire .021” Diameter

IV. Weld Geometries

Lap Joints - .010” to .010” Kovar to Kovar sheet stock
Lap Joints - .021” Dia. Nickel 201Wire to .010” Kovar sheet stock
Lap Joints - .021” Dia. Wire Kovar to .010” Sheet stock
Maximum/Minimum gap experimentation – Lap welds with gaps purposely introduced within joint fit-up

V. Analytical Characterization

Light microscopy – metallograpy:
a) macro photos to document geometry, weld appearance, overall configuration
b) mount, polish grind to center line of weld, acid etch to reveal fusion zone
c) inspect fusion zone for depth of penetration, evidence of micro cracking, inspect for voids or inclusion

Mechanical testing – Tensile test to determine yield strength:
a) Tinius Olsen Lo-Cap tensile tester
Ductility testing:

a) Samples were hand bent 90 and 180 degrees from normal joint configuration with weld nugget not failing illustrating ductility of weld bead. Weld was still intact after manual bending operation. Weld coupons were photographed to document ductility experiment.

VI. Weld Schedules

Weld schedules were determined by the Design of Experiment conditions listed on page A1. Weld processing factors include the following:

Angle of Attack. The actual processing angle, determined by hard/rigid weld fixtures or tooling.
Volts. V-/V+ Reference value for the voltage. The voltage influences the height of the laser pulse and consequently the depth of the welding point or molten weld pool.
Pulse. Reference value for the duration of the laser pulse (ms-/ms+ milli-seconds). This affects the diameter of the welding point.
Focus. 0-/0+ Focus setting: This changes the diameter of the focal spot.

The experimental results for Lap Joints, Nickel-Wire Joints, and Kovar-Wire Joints follow below.

Experimental Results for Lap Joints

The results for Lap Joints are given on pages A4-A15 of Appendix A. Page A4 shows the main effects plot for Break Strength. This graph gives the average response at each of the three levels for each experimental factor. It is used to compare the relative effects of the four factors on Breaking Strength. It also suggests whether each factor has a linear or quadratic effect on the response variable. Page A5 shows the two-way interaction plots associated with the four factors. Parallel lines in the interaction plots indicate little or no interaction, while non-parallel lines indicate presence of interaction. The main effects and interaction plots can be used to suggest what terms should be included in the fitted model relating these factors to Breaking Strength. The best fitted model identified for these data is given on page A6. Note that this model includes four linear terms, three pure quadratic terms, and three two-way interaction terms. This model fits the data reasonably well, with an R-square value of 70%. The experimental repeatability standard deviation is approximately 7.5 lbs., and the standard deviation of the fitted values is 3.5 lbs. This means that any fitted value from the model will be within $\pm$ 7 lbs. (two standard deviations) of the actual value with 95% confidence.

Page A7 shows the contour plot for Angle of Attack and Volts, with Pulse Length and Focus held constant at 2.0 ms and 17.0 respectively. Page A8 shows the contour plot for Pulse Length and Focus, with Angle of Attack and Volts held constant at 45 degrees and 330 volts respectively. The factors were held constant at these levels to reflect the final weld condition chosen for production. Discussion below concerns how the overall optimum is chosen and how these contour plots are used to define an operating window for the four processing factors.

Page A9 shows the plot of Breaking Strength vs. visual Rating. These two response variables have a positive correlation, but it is not great (sample correlation r = .44). Thus optimizing the process for one of the response variables need not yield the optimum for the second response variable.

Page A10 shows the main effects plot for Rating (1-5 visual rating). This graph gives the average response at each of the three levels for each experimental factor. It is used to compare the relative effects of the four factors on Rating. It also suggests whether each factor has a linear or quadratic effect on the response variable. Page A11 shows the two-way interaction plots associated with the four factors. Parallel lines in the interaction plots indicate little or no interaction, while non-parallel lines indicate presence of interaction. Note that a few of the plots suggest interaction may be present. The main effects and interaction plots can be used to suggest what terms should be included in the fitted model relating these factors to Rating. The best fitted model identified for these data is given on page A12. Note that this model includes four linear terms, one pure quadratic term, and three two-way interaction terms. This model fits the data well, with an R-square value of 80%. The experimental repeatability standard deviation is approximately .60, and the standard deviation of the fitted values is .30. This means that any fitted value from the model will be within $\pm$ .60 of the actual value with 95% confidence.

Page A13 shows the contour plot for Angle of Attack and Volts, with Pulse Length and Focus held constant at 2.0 ms and 17.0 respectively. Page A14 shows the contour plot for Pulse Length and Focus, with Angle of Attack and Volts held constant at 45 degrees and 330 volts respectively. The factors were held constant at these levels to reflect the final weld condition chosen for production. Page A15 gives the multiple response optimization performed by Minitab for Lap Joints. The optimizer uses analytical techniques to jointly optimize Breaking Strength and Rating. The result is a compromise solution that does not optimize either response individually, but achieves a joint optimization. That is, the optimum setting identified is one for which both responses end up very close to their individual optimums. In this case the overall optimum solution for Lap joints is (Angle = 35, Volts = 345, Pulse = 2.5, and Focus = 20). This results in a predicted Breaking Strength of 79 lbs. and a rating of 5.0. From the original data we can see that the single best experimental condition was at (Angle = 30, Volts = 350, Pulse = 2.5 and Focus = 20) with an average Breaking strength of 80 lbs. and a rating of 5. Thus the predicted optimum based on the fitted models for Breaking Strength and Rating is consistent with the best observed condition.

The contour plots on pages A7, A8, A13 and A14 can also be used to define operating windows for the four process factors. The operating window is the range of values for each factor that can be used in laser weld processing without seriously degrading the breaking strength or visual quality of the weld. From page A7 and A13, an operating window for Angle of Attack is 30-50 degrees, and an operating window for Volts is 330-350 volts. From page A8 and A14 we can see that the operating window for Pulse Length and Focus is not as wide. An operating window for Pulse Length is 1.9-2.5 ms and an operating window for Focus is 16-20. It should be pointed out that no pulse lengths greater than 2.5 were tried and no Focus values greater than 20 were tried in this experiment.

Experimental Results for Nickel-Wire Joints

The results for Nickel-Wire Joints (abbreviated NiWire in the analyses) are given on pages A16-A27 of Appendix A. Page A16 shows the main effects plot for Breaking Strength. This graph gives the average response at each of the three levels for each experimental factor. It is used to compare the relative effects of the four factors on Breaking Strength. It also suggests whether each factor has a linear or quadratic effect on the response variable. Page A17 shows the two-way interaction plots associated with the four factors. The best fitted model identified for these data is given on page A18. Note that this model includes four linear terms, four pure quadratic terms, and two two-way interaction terms. This model fits the data very well, with an R-square value of 87%. The experimental repeatability standard deviation is approximately 1.6 lbs., and the standard deviation of the fitted values is 1.2 lbs. This means that any fitted value from the model will be within ± 2.4 lbs. of the actual value with 95% confidence.

Page A19 shows the contour plot for Angle of Attack and Volts, with Pulse Length and Focus held constant at 2.0 ms and 17.0 respectively. Page A20 shows the contour plot for Pulse Length and Focus, with Angle of Attack and Volts held constant at 45 degrees and 330 volts respectively. The factors were held constant at these levels to reflect the final weld condition chosen for production.

Page A21 shows the plot of Breaking Strength vs. Rating. For NiWire Joints, these two response variables have essentially no correlation (sample correlation r = -.15). Thus optimizing the process for one of the response variables need not yield the optimum for the second response variable.

Page A22 shows the main effects plot for Rating (1-5 visual rating). This graph gives the average response at each of the three levels for each experimental factor. It is used to compare the relative effects of the four factors on Rating. It also suggests whether each factor has a linear or quadratic effect on the response variable. Page A23 shows the two-way interaction plots associated with the four factors. Note that a few of the two-way plots suggest interaction may be present. The best fitted model identified for these data is given on page A24. Note that this model includes four linear terms, two pure quadratic terms, and two two-way interaction terms. This model fits the data reasonably well, with an R-square value of 70%. The experimental repeatability standard deviation is approximately .50, and the standard deviation of the fitted values is .35. This means that any fitted value from the model will be within ± .70 of the actual value with 95% confidence.

Page A25 shows the contour plot for Angle of Attack and Volts, with Pulse Length and Focus held constant at 2.0 ms and 17.0 respectively. Page A26 shows the contour plot for Pulse Length and Focus, with Angle of Attack and Volts held constant at 45 degrees and 330 volts respectively. The factors were held constant at these levels to reflect the final weld condition chosen for production. Page A27 gives the multiple response optimization performed by Minitab for NiWire Joints. The optimizer uses analytical techniques to jointly optimize Breaking Strength and Rating. The result is a compromise solution that does not optimize either response individually, but achieves a joint optimization. That is, the optimum setting identified is one for which both responses end up very close to their individual optimums. In this case the overall optimum solution for NiWire joints is (Angle = 46, Volts = 332, Pulse = 2.0, and Focus = 16). This results in a predicted Breaking Strength of 29 lbs. and a rating of 4.3. From the original data we can see that the single best experimental condition was at (Angle = 45, Volts = 330, Pulse = 2.0 and Focus = 16) with a Breaking Strength of 29 lbs. and a rating of 5. So the predicted optimum based on the models for Breaking Strength and Rating is consistent with the best observed condition.

The contour plots on pages A19, A20, A25 and A26 can be used to define operating windows for the four process factors. From pages A19 and A25, an operating window for Angle of Attack is 40-60 degrees, and an operating window for Volts is 320-350 volts. From pages A20 and A26, an operating window for Pulse Length is 1.8-2.4 ms and an operating window for Focus is 16-20. It should be pointed out that no pulse lengths greater than 2.5 were tried and no Focus values less than 16 were tried in this experiment.

<u>Experimental Results for Kovar-Wire Joints</u>

The results for Kovar-Wire Joints (abbreviated KoWire in the analyses) are given on pages A28-A39 of Appendix A. Page A28 shows the main effects plot for Breaking Strength. This graph gives the average response at each of the three levels for each experimental factor. It is used to compare the relative effects of the four factors on Breaking Strength. It also suggests whether each factor has a linear or quadratic effect on the response variable. Page A29 shows the two-way interaction plots associated with the four factors. The best fitted model identified for these data is given on page A30. Note that this model includes four linear terms, three pure quadratic terms, and two two-way interaction terms. This model fits the data very well, with an R-square value of 84%. The experimental repeatability standard deviation is approximately 1.4 lbs., and the standard deviation of the fitted values is 0.70 lbs. This means that any fitted value from the model will be within $\pm$ 1.4 lbs. of the actual value with 95% confidence.

Page A31 shows the contour plot for Angle of Attack and Volts, with Pulse Length and Focus held constant at 2.0 ms and 17.0 respectively. Page A32 shows the contour plot for Pulse Length and Focus, with Angle of Attack and Volts held constant at 45 degrees and 330 volts respectively. The factors were held constant at these levels to reflect the final weld condition chosen for production.

Page A33 shows the plot of Breaking Strength vs. Rating. For KoWire Joints, these two response variables do not have a strong correlation (sample correlation $r = .47$). Thus optimizing the process for one of the response variables need not yield the optimum for the second response variable.

Page A34 shows the main effects plot for Rating (1-5 visual rating). This graph gives the average response at each of the three levels for each experimental factor. It is used to compare the relative effects of the four factors on Rating. It also suggests whether each factor has a linear or quadratic effect on the response variable. Page A35 shows the two-way interaction plots associated with the four factors. Note that a few of the two-way plots suggest interaction may be present. The best fitted model identified for these data is given on page A36. Note that this model includes four linear terms, two pure quadratic terms, and two two-way interaction terms. This model fits the data very well, with an R-square value of 92%. The experimental repeatability standard deviation is approximately .27, and the standard deviation of the fitted values is .20. This means that any fitted value from the model will be within $\pm$ .40 of the actual value with 95% confidence.

Page A37 shows the contour plot for Angle of Attack and Volts, with Pulse Length and Focus held constant at 2.0 ms and 17.0 respectively. Page A38 shows the contour plot for Pulse Length and Focus, with Angle of Attack and Volts held constant at 45 degrees and 330 Volts respectively. The factors were held constant at these levels to reflect the final weld condition chosen for production.

Page A39 gives the multiple response optimization performed by Minitab for KoWire Joints. The optimizer uses analytical techniques to jointly optimize Breaking Strength and Rating. The result is a compromise solution that does not optimize either response individually, but achieves a joint optimization. That is, the optimum setting identified is one for which both responses end up very close to their individual optimums. In this case the overall optimum solution for KoWire joints is (Angle = 45, Volts = 330, Pulse = 2.0, and Focus = 20). This results in a predicted Breaking Strength of 35 lbs. and a rating of 4.6. From the original data we can see that the single best experimental condition was at (Angle = 45, Volts = 330, Pulse = 2.0 and Focus = 20) with a Breaking Strength of 34.6 lbs. and a rating of 4.5. So the predicted optimum based on the models for Breaking Strength and Rating is consistent with the single best condition.

The contour plots on pages A31, A32, A37 and A38 can also be used to define operating windows for the four process factors. From pages A31 and A37, an operating window for Angle of Attack is 35-55 degrees, and an operating window for Volts is 310-340 volts. From pages A32 and A38, an operating window for Pulse Length is 1.5-2.2 ms and an operating window for Focus is 16-20. It should be pointed out that no pulse lengths greater than 2.5 were tried and no Focus values greater than 20 were tried in this experiment.

Optimal Condition and Operating Windows

The models developed for each weld type and the resulting contour plots were used to identify optimal conditions and operating windows for each weld type. The optimal condition is the choice of levels for the process factors that maximizes the breaking strength and rating response variables jointly. The operating window is the range of values for each factor that can be used in laser weld processing without seriously degrading the breaking strength or visual quality of the weld. Identification of operating windows is somewhat subjective, but the contour plots, along with knowledge of breaking strength requirements, can be used to provide reasonable bounds for each factor.

The optimum solution identified (see A15) for Lap joints alone is (Angle = 35, Volts = 345, Pulse = 2.5, and Focus = 20). For Lap Joints, an operating window for Angle of Attack is 30-50 degrees, an operating window for Volts is 330-350 volts, an operating window for Pulse Length is 1.9-2.5 ms and an operating window for Focus is 16-20.

The optimum solution identified (see A27) for NiWire joints alone is (Angle = 46, Volts = 332, Pulse = 2.0, and Focus = 16). For NiWire Joints, an operating window for Angle of Attack is 40-60 degrees, an operating window for Volts is 320-350 volts, an operating window for Pulse Length is 1.8-2.4 ms and an operating window for Focus is 16-20.

The optimum solution identified (see A39) for KoWire joints alone is (Angle = 45, Volts = 330, Pulse = 2.0, and Focus = 20). For KoWire joints, an operating window for Angle of Attack is 35-55 degrees, an operating window for Volts is 310-340 volts, an operating window for Pulse Length is 1.5-2.2 ms and an operating window for Focus is 16-20. The operating windows for each weld type are given on Page A40.

During the course of assembling a power supply for the MC4368A, a number of different weld joints must be made. To minimize possible incorrect entry of weld schedules into the A-B system by an operator, it is desirable to identify a single weld schedule that will provide acceptable results for all the varying conditions including angles, material thickness, etc. If we use the multiple response optimization technique for all six responses (3 weld types, 2 responses each) simultaneously (see A41) the single best overall condition is:

(Angle of Attack = 35, Volts = 340, Pulse Length = 2.4, Focus = 19.5).

If the importance rating (determined by the process engineer) for the Lap Weld is twice the importance rating for the other two weld types the optimal condition becomes:

(Angle of Attack = 30, Volts = 340, Pulse Length = 2.4, Focus = 19.5).

The multiple response optimization technique finds an overall "best" operating condition. That condition typically ends up being a compromise between the individual weld optimal conditions. If the importance rating for one weld type is greater than that for the other welds, the overall best condition will be closer to the optimal condition for that weld type.

The weld condition that was decided upon for production differed slightly from the optimal condition identified above. A weld condition of

(Volts = 330, Pulse Length = 2.0, Focus = 17.0)

was chosen instead, for several reasons. First, an extensive development study prior to the formal DOEx showed that this condition would produce excellent welds of each type. Second, these results fit into the operating windows identified by the present experiment. Finally, it was felt that 340 Volts caused the process to approach or exceed the upper bounds on the penetration limit (measured by the visual rating), and the desire was to be somewhat conservative. For the remaining factor, Angle of Attack, the most common angle encountered in production is 45 degrees.

Discussion and Conclusions

The design of experiments (DOEx) approach was used to characterize the Laser Weld process with respect to four processing factors: Angle of Attack, Volts, Pulse Length, and Focus. The experiment was performed with Lap Joints, Nickel-Wire Joints, and Kovar-Wire Joints. For each weld type an individual optimal condition and operating window was identified. The widths of the operating windows that were identified by experimentation indicate that the laser weld process is very "robust". A robust process is highly desirable because it means that the quality of the resulting welds is not sensitive to the exact values of the processing factors within the operating window. To keep the break strength or visual quality from seriously degrading it is recommended that statistical process control techniques be used to ensure that the processing factors stay well within the operating window.

With respect to strength, the vast majority of the processing factor combinations gave adequate strength results and correspondingly adequate electrical current carrying capabilities. In fact, independent experimentation had shown that even very poor welds would pass the electrical tests, so electrical parameters were not considered key response variables for the present experiment. Furthermore, the weld bead appearance was acceptable in most cases. Therefore, parameters were chosen that would preclude, as much as possible, a major failure mode, i.e., burn through, from occurring. The parameters were chosen that gave the most margin for error while at the same time ensuring that the weld strength would be adequate.

The resultant operating factors were chosen and have been inserted into the appropriate Work Instruction (WI). The process engineers and technicians will have the larger operating window for each factor available to them should there be any degradation of laser power due to lamp aging. Also, should there be any changes in weld appearance upon examination by the operators on the floor any individual or combination of factors may be changed within the comprehensive range of acceptable weld operating conditions.

Reference

Box, G. E. P. and N. R. Draper (1987). Empirical Model Building and Response Surfaces. John Wiley and Sons, NY.

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Appendix A – Statistical Analysis of Laser Weld Experiment

Appendix B – Metallography of Laser Weld Samples

Distribution

1	MS0521	Bacon, Frank, 2502
1	MS0515	Barnhart, Steve, 2561
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10	MS0829	Crowder, Stephen, 12323
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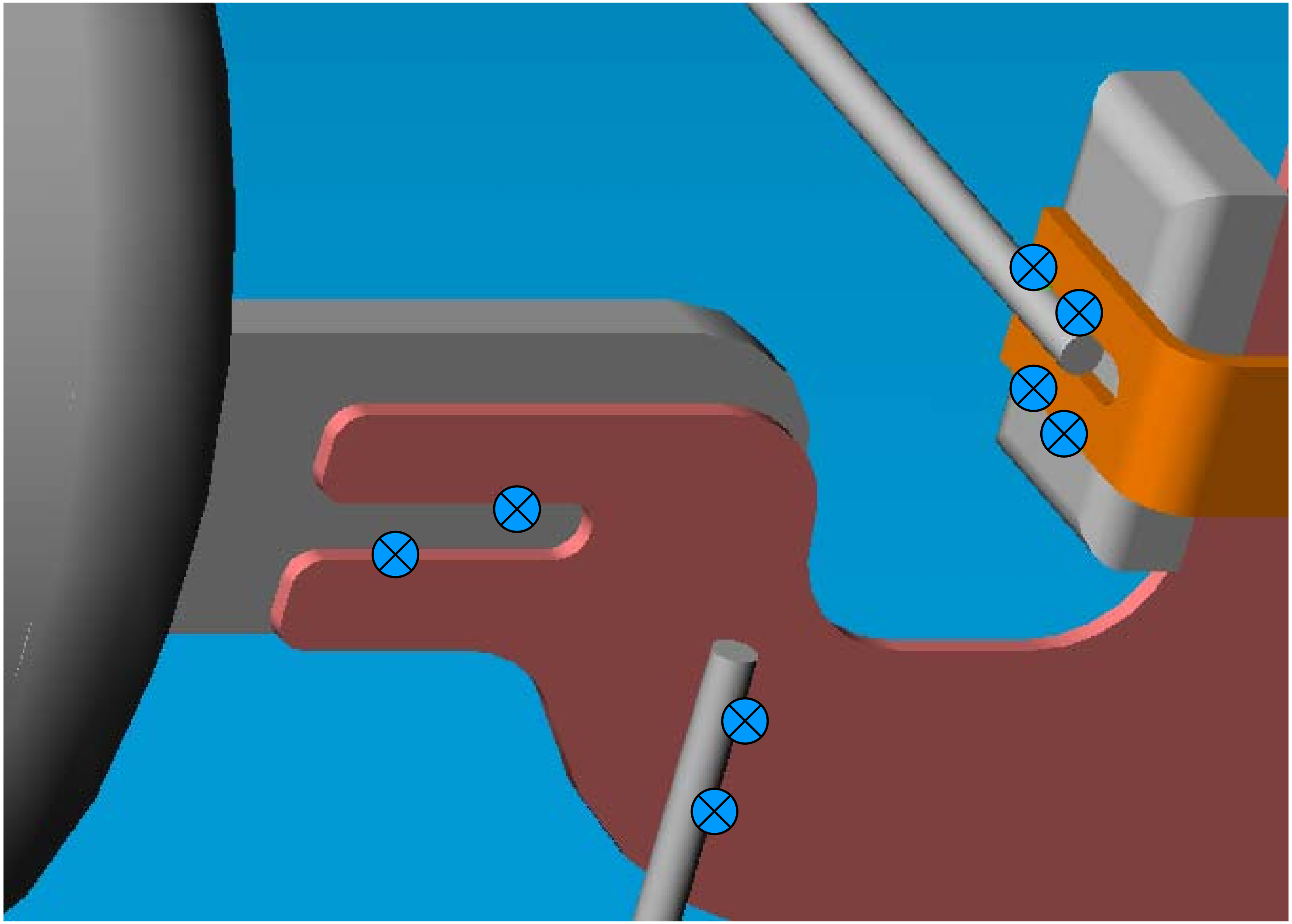
Laser Weld Design of Experiments

Run	Angle of Attack	Volts	Pulse Length (ms)	Focus
1	30	310	1.5	16
2	60	310	1.5	16
3	30	350	1.5	16
4	60	350	1.5	16
5	30	310	2.5	16
6	60	310	2.5	16
7	30	350	2.5	16
8	60	350	2.5	16
9	30	310	1.5	20
10	60	310	1.5	20
11	30	350	1.5	20
12	60	350	1.5	20
13	30	310	2.5	20
14	60	310	2.5	20
15	30	350	2.5	20
16	60	350	2.5	20
17	30	330	2.0	18
18	60	330	2.0	18
19	45	310	2.0	18
20	45	350	2.0	18
21	45	330	1.5	18
22	45	330	2.5	18
23	45	330	2.0	16
24	45	330	2.0	20
25	45	330	2.0	18

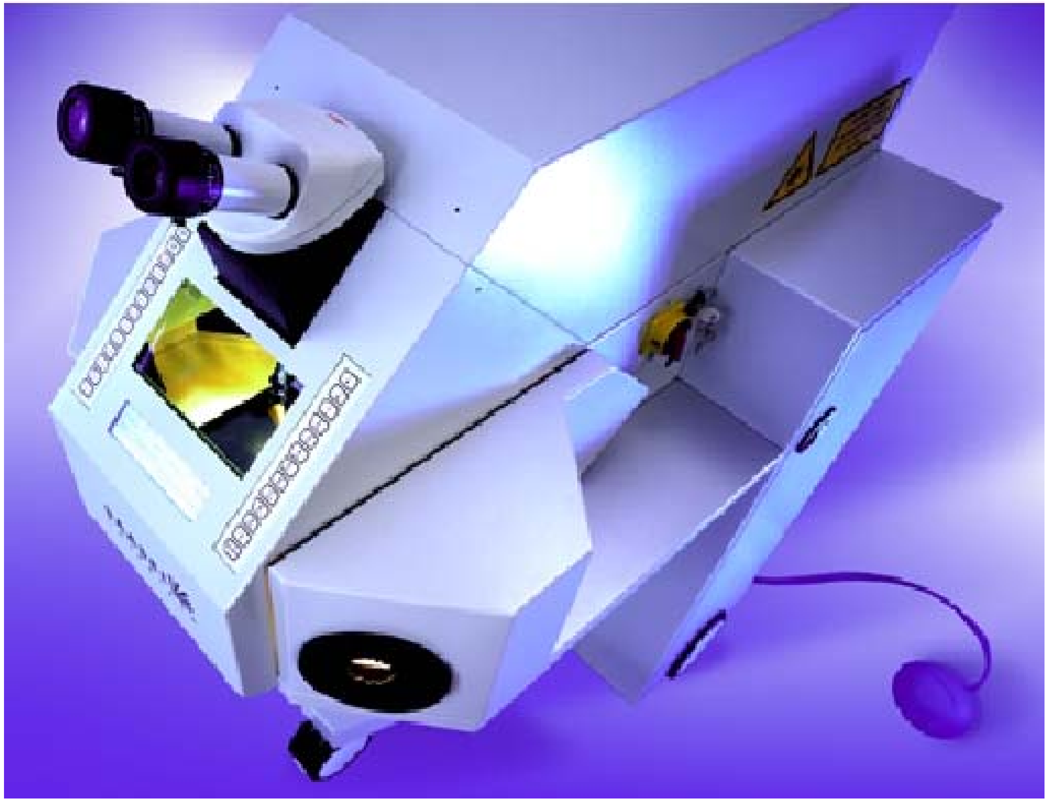
These combinations were run for Lap joints (Kovar sheet to Kovar sheet), NiWire joints (Nickel wire to Kovar sheet), and KoWire joints (Kovar wire to Kovar sheet). Each combination was run twice with Lap joints, twice with KoWire joints and once with NiWire joints.

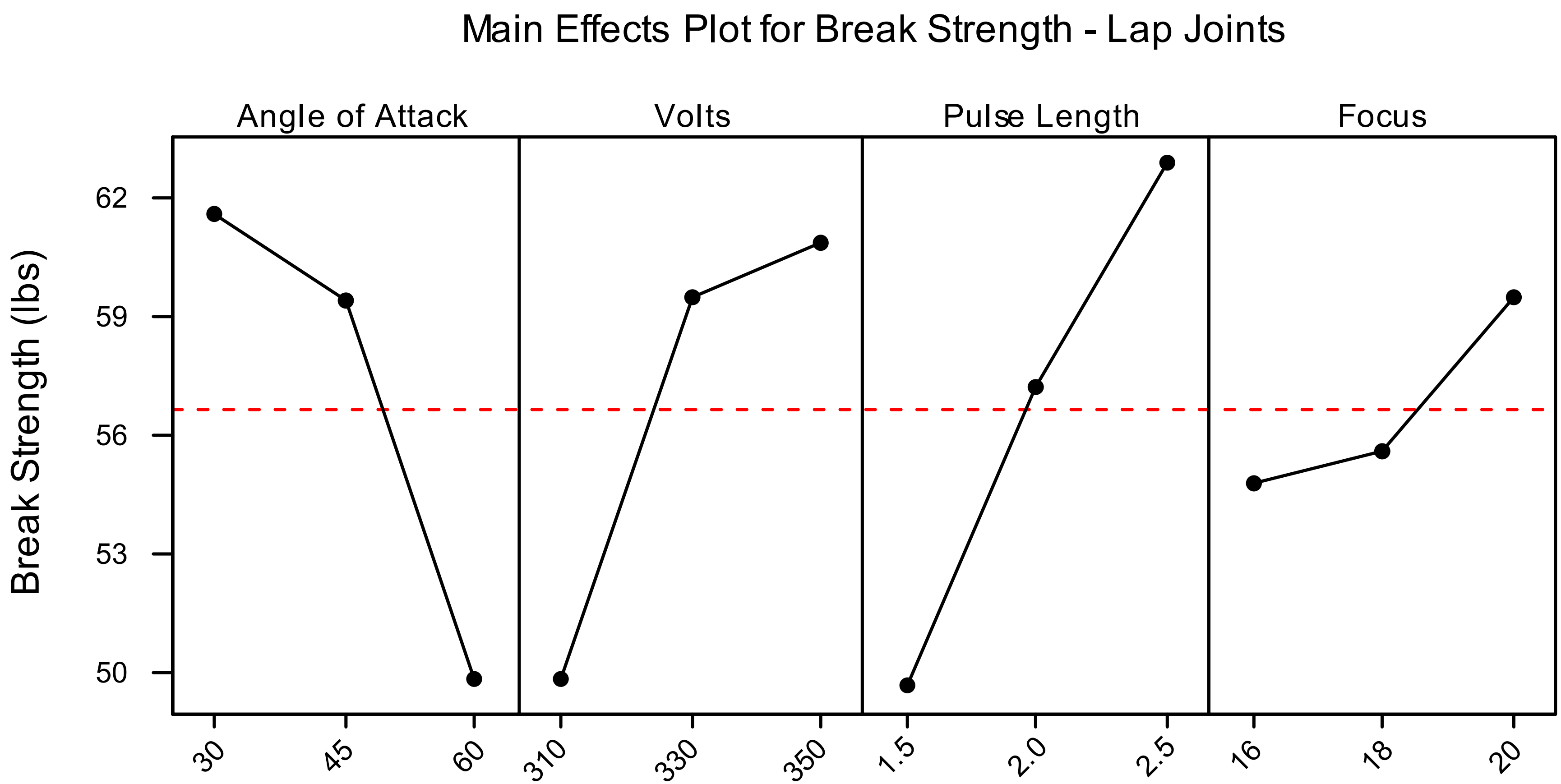
Examples of Spot Weld Geometries



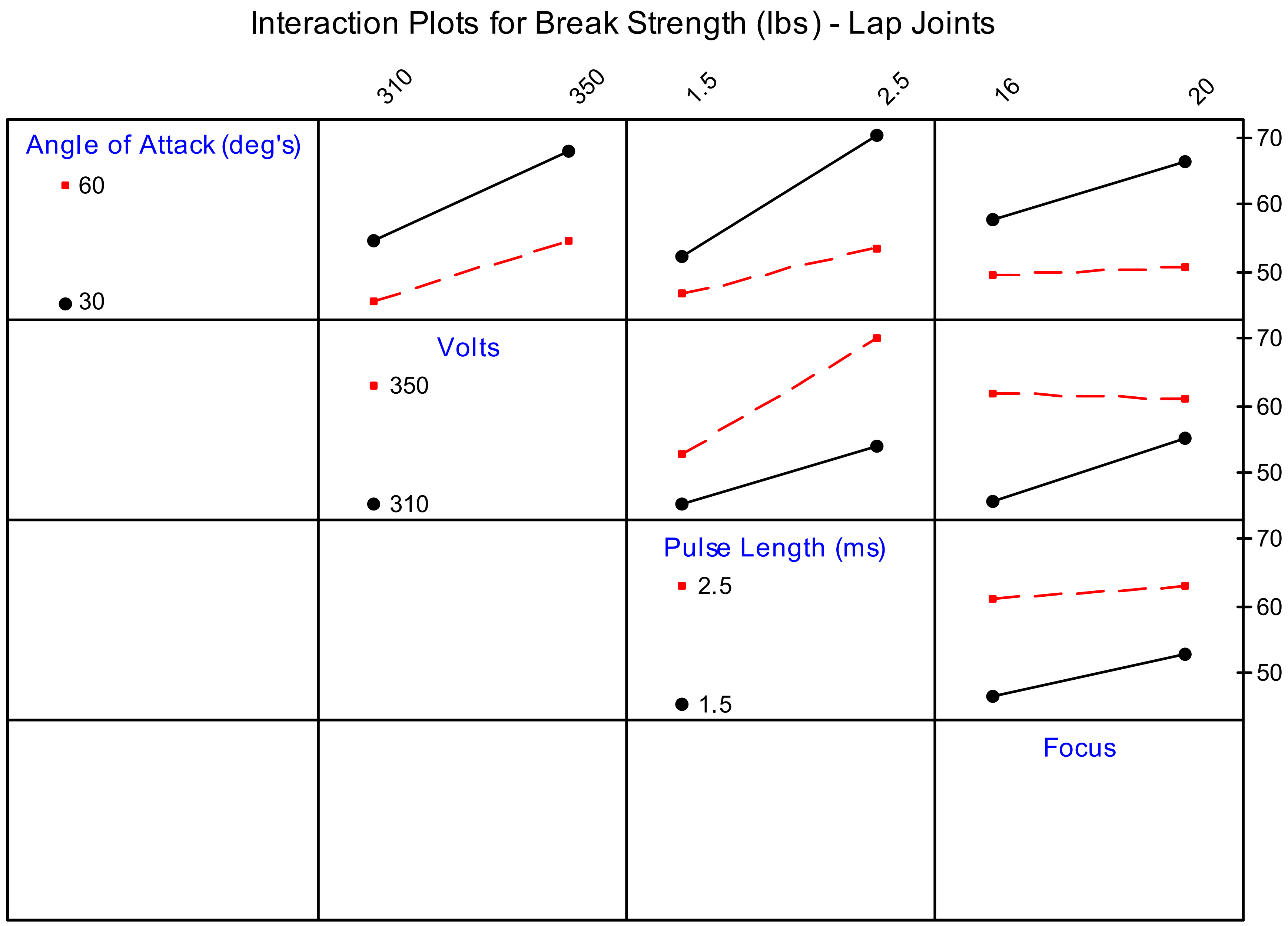
Equipment Used in the DOEx

- Laser Welder:
  - A-B SWP 5002
- MacGregor DC2000 power supply & Unitek Model 127 parallel gap head for pulse testing
- Nicolet Pro-10 & LeCroy 9314M Oscilloscopes
- Tinius-Olsen Lo-Cap tensile tester




Main Effects Plot for Break Strength - Lap Joints
Angle of Attack
Volts
Pulse Length
Focus
Break Strength (lbs)
62
59
56
53
50
30
45
60
310
330
350
1.5
2.0
2.5
16
18
20

A4


Interaction Plots for Break Strength (lbs) - Lap Joints
310
350
1.5
2.5
16
20
Angle of Attack (deg's)
60
30
Volts
350
310
Pulse Length (ms)
2.5
1.5
Focus
70
60
50

A5

Response Surface Regression for Break Strength - Lap Joints

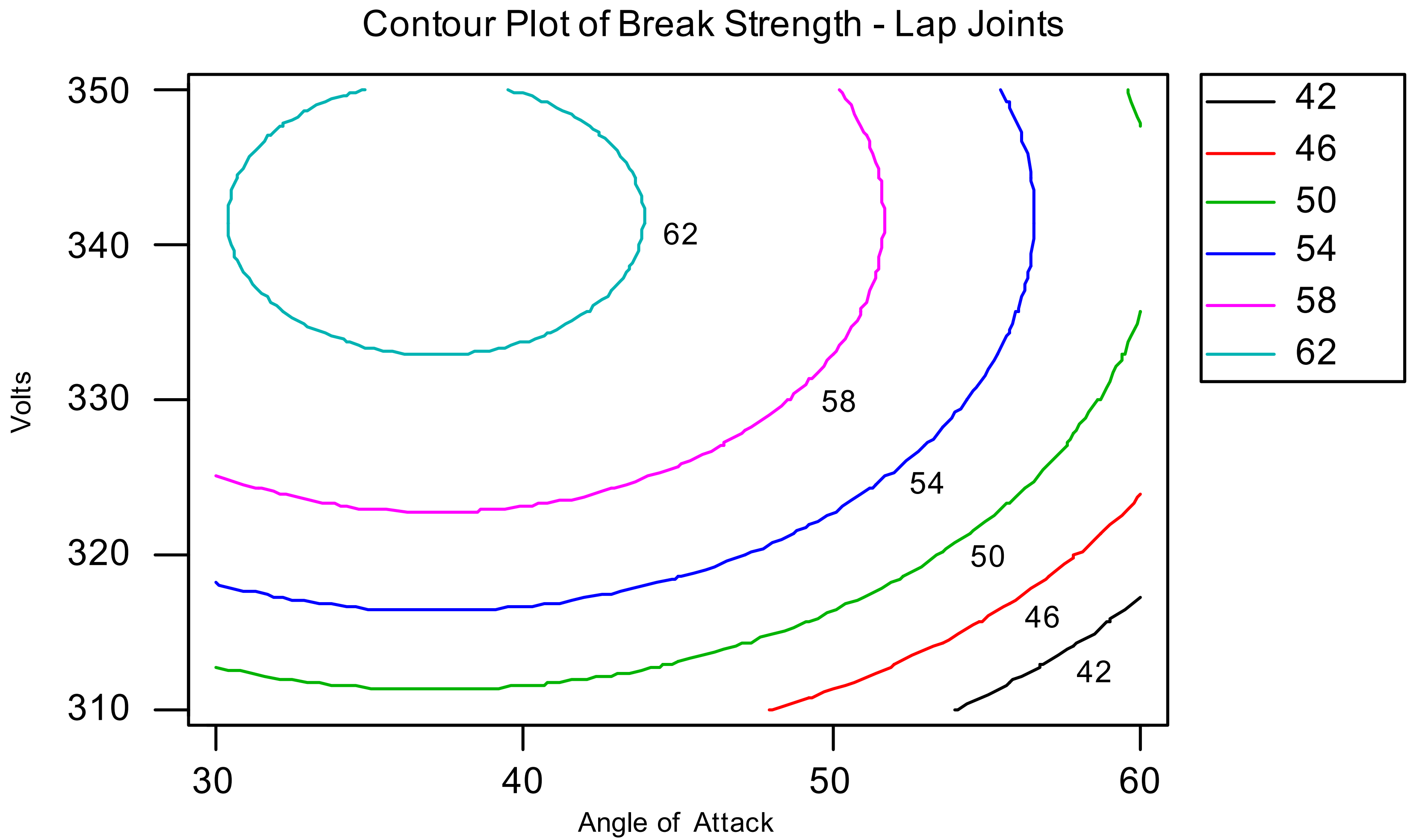
The analysis was done using coded units.

Estimated Regression Coefficients for Break Strength

Term	**Coef**	**StDev**	**T**	**P**
Constant	58.730	2.276	25.809	0.000
Angle of Attack	-5.684	1.287	-4.416	0.000
Volts	5.416	1.287	4.209	0.000
Pulse Length	6.503	1.287	5.053	0.000
Focus	2.192	1.287	1.703	0.097
Angle*Angle	-5.415	3.235	-1.674	0.102
Volts*Volts	-5.665	3.235	-1.751	0.088
Focus*Focus	8.110	3.235	2.507	0.017
Angle*Pulse Length	-2.715	1.368	-1.985	0.054
Volts*Pulse Length	2.360	1.368	1.725	0.093
Volts*Focus	-2.447	1.368	-1.789	0.082

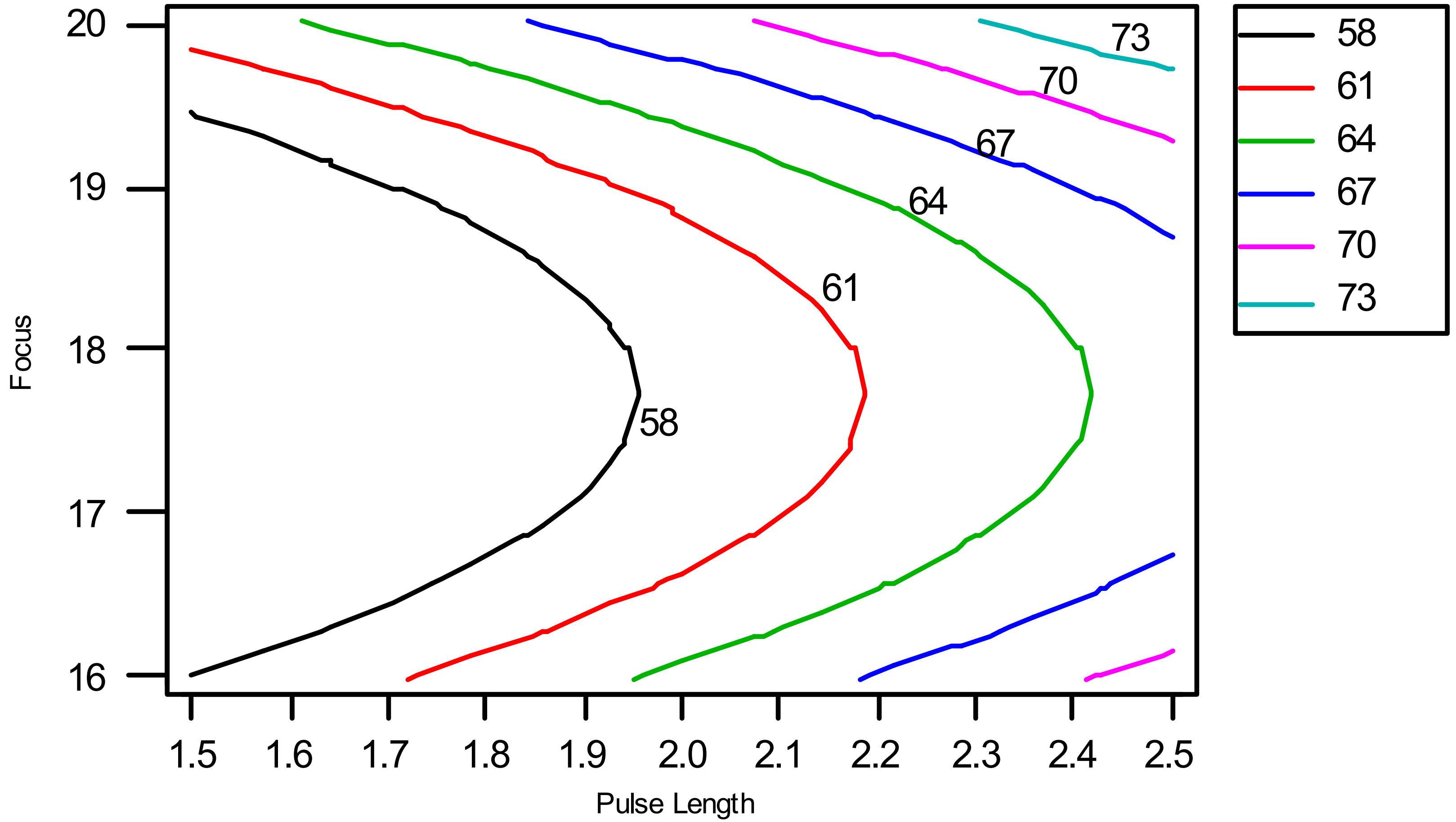
S = 7.585 R-Sq = 69.9%

Standard Deviation of Fits = 3.5

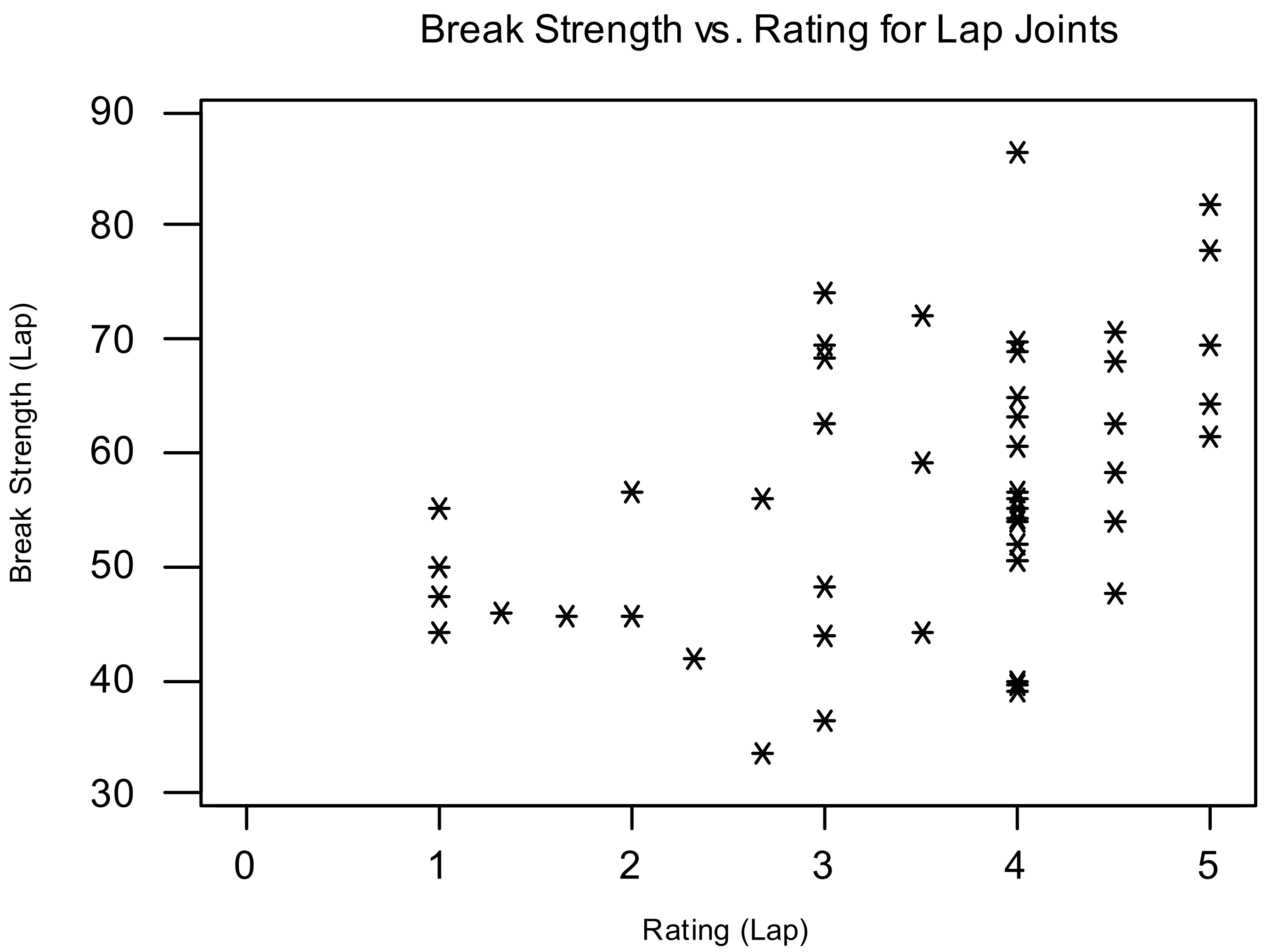


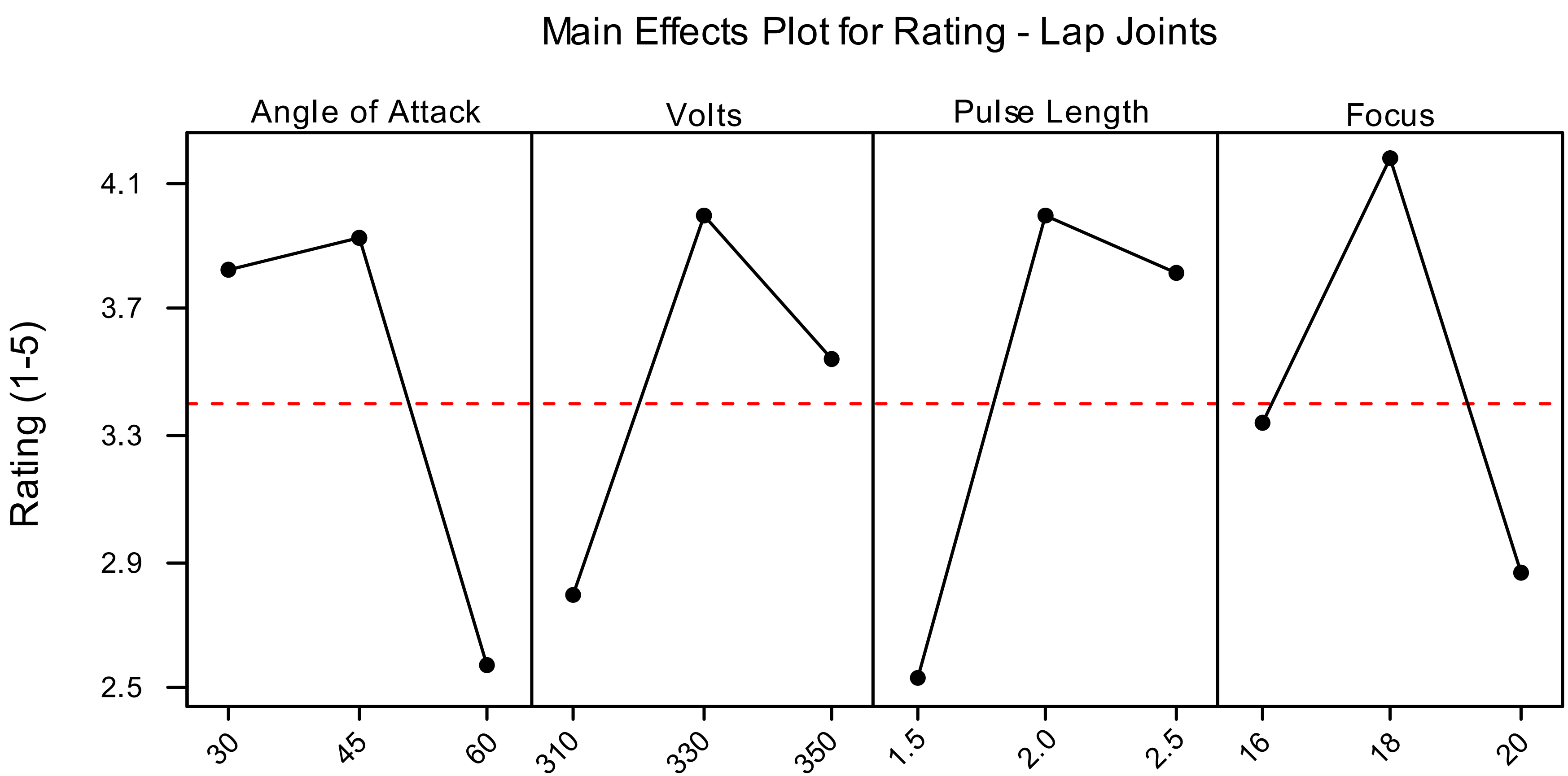
Hold values: Pulse Length: 2.0 Focus: 17.0

Contour Plot of Break Strength - Lap Joints



Hold values: Angle of Attack: 45.0 Volts: 330.0


Break Strength vs. Rating for Lap Joints
90
80
70
60
50
40
30
Break Strength (Lap)
0
1
2
3
4
5
Rating (Lap)


Main Effects Plot for Rating - Lap Joints
Angle of Attack
Volts
Pulse Length
Focus
Rating (1-5)
4.1
3.7
3.3
2.9
2.5
30
45
60
310
330
350
1.5
2.0
2.5
16
18
20

Interaction Plots for Rating - Lap Joints
310
350
1.5
2.5
16
20
Angle of Attack
60
30
Volts
350
310
Pulse Length
2.5
1.5
Focus
4
3
2

Response Surface Regression for Rating - Lap Joints

The analysis was done using coded units.

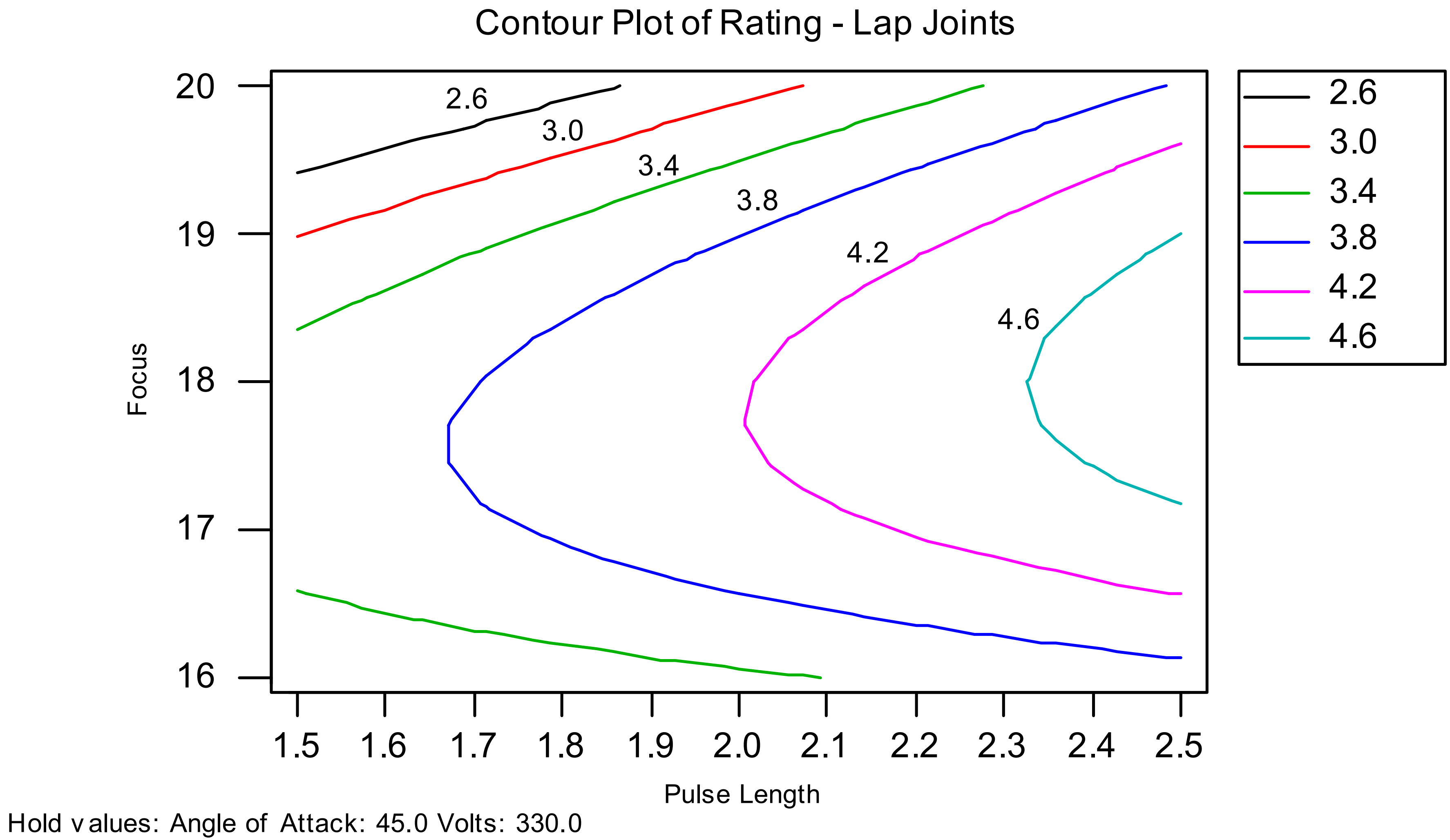
Estimated Regression Coefficients for Rating

Term	**Coef**	**StDev**	**T**	**P**
Constant	4.179	0.1623	25.752	0.000
Angle of Attack	-0.625	0.1012	-6.174	0.000
Volts	0.375	0.1012	3.703	0.001
Pulse Length	0.644	0.1012	6.361	0.000
Focus	-0.241	0.1012	-2.380	0.022
Focus*Focus	-1.077	0.1912	-5.630	0.000
Angle*Volts	-0.214	0.1073	-1.995	0.053
Volts*Focus	0.485	0.1073	4.516	0.000
Pulse Length*Focus	0.328	0.1073	3.060	0.004

S = 0.6071   R-Sq = 79.9%

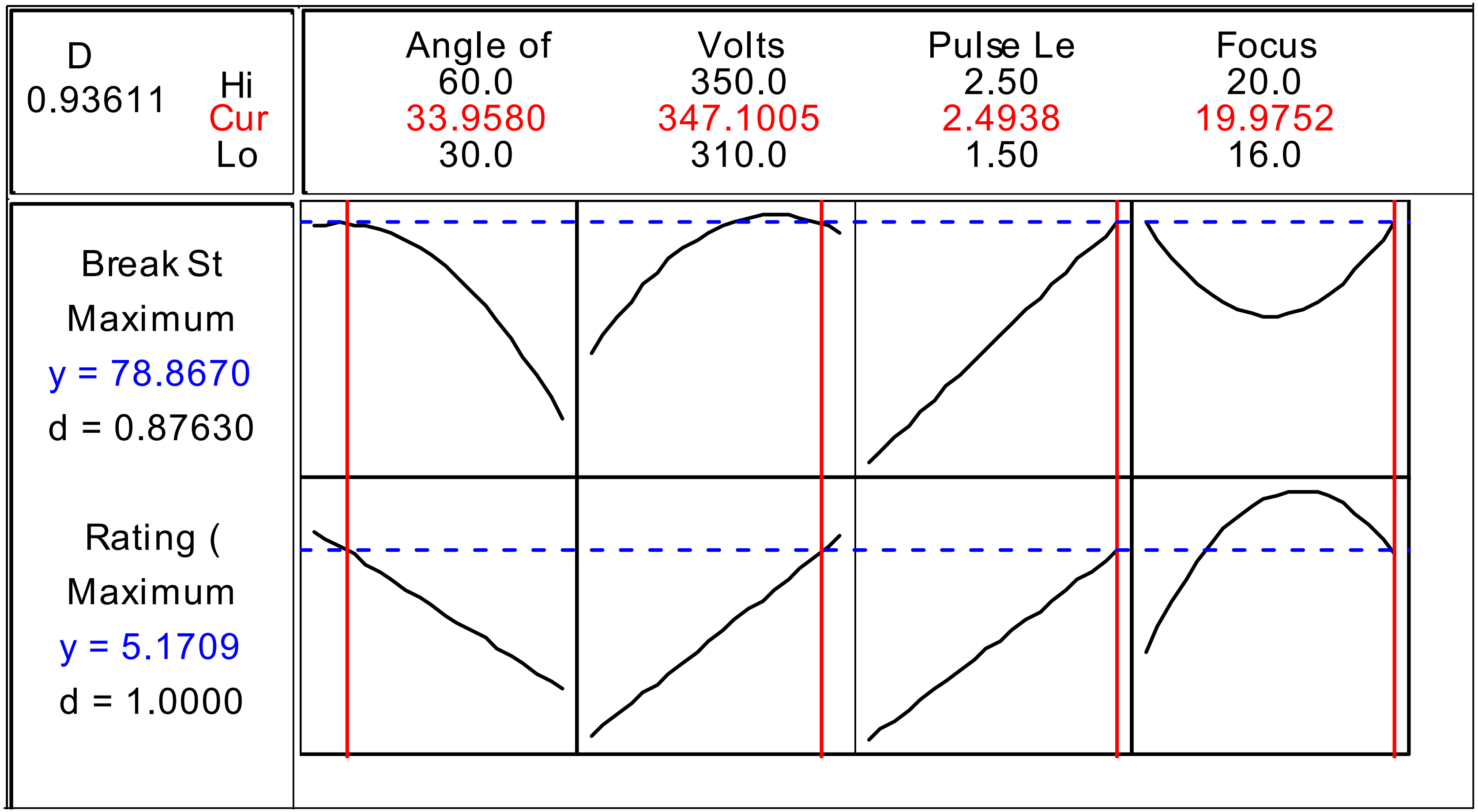
Standard Deviation of Fits = .30


Contour Plot of Rating - Lap Joints
350
340
330
320
310
Volts
30
40
50
60
Angle of Attack
4.7
4.5
4.3
4.1
3.9
3.7
Hold values: Pulse Length: 2.0 Focus: 17.0

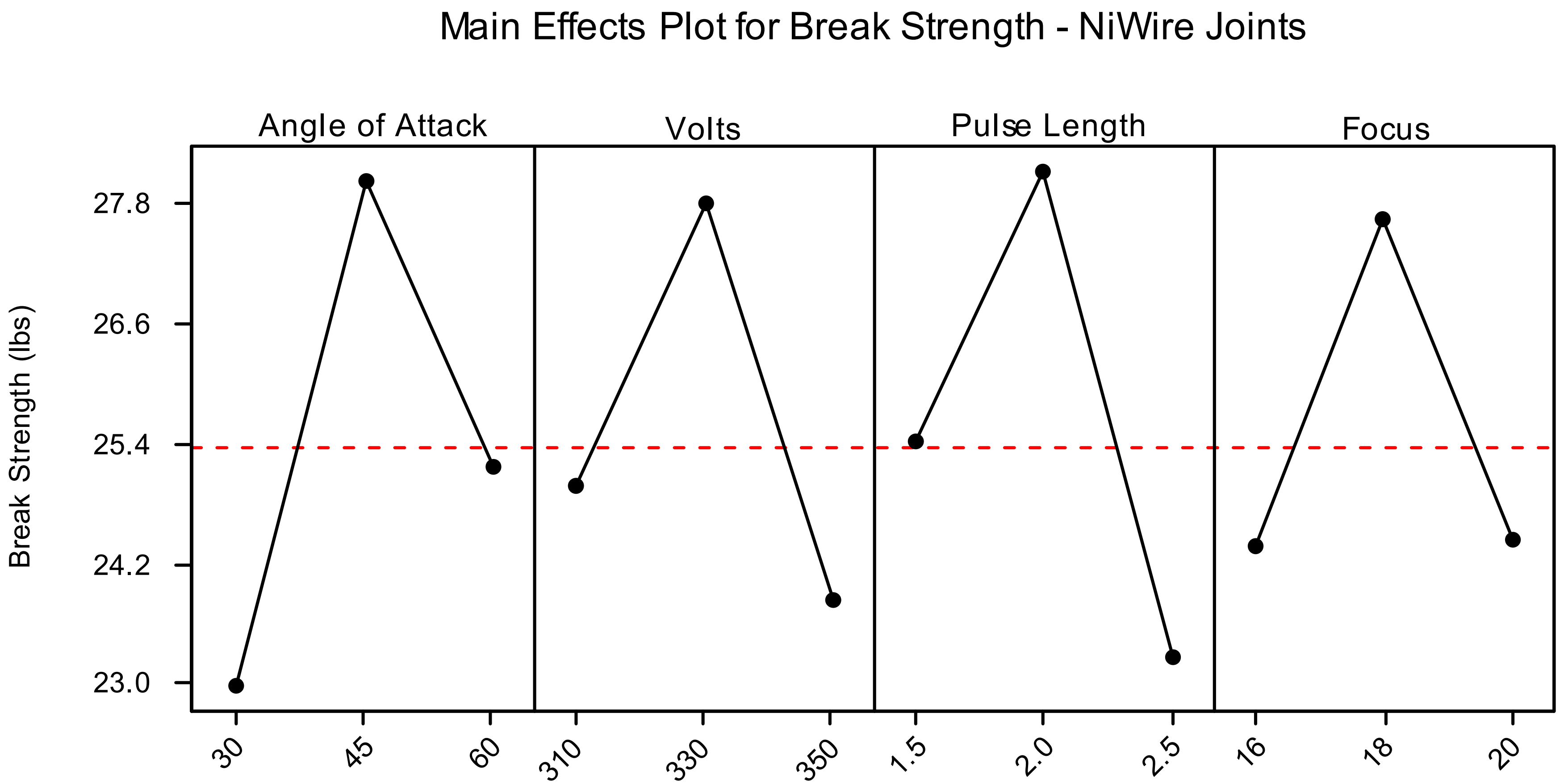


Contour Plot of Rating - Lap Joints
20
19
18
17
16
Focus
2.6
3.0
3.4
3.8
4.2
4.6
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
Pulse Length
2.6
3.0
3.4
3.8
4.2
4.6
Hold values: Angle of Attack: 45.0 Volts: 330.0

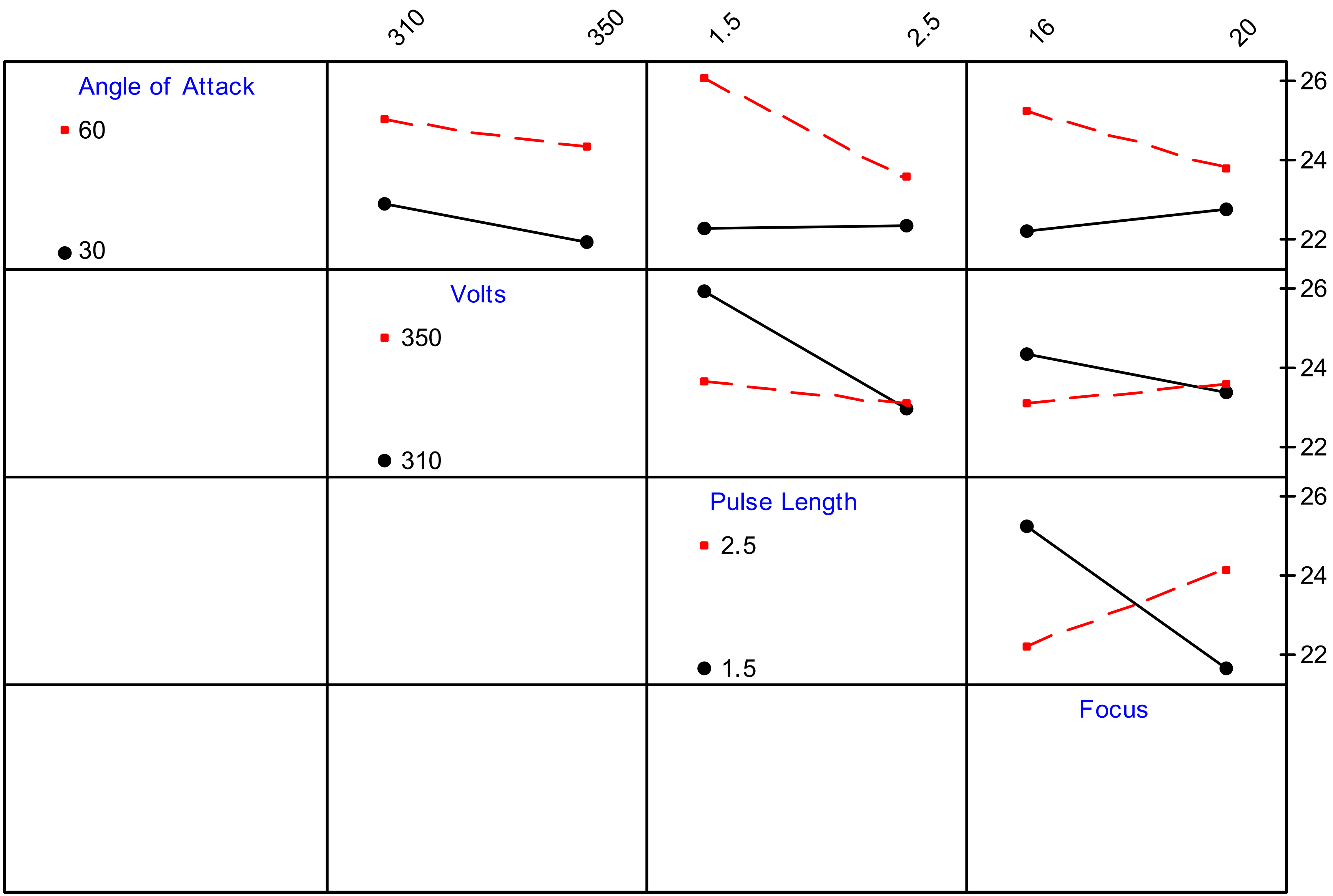
Multiple Response Optimizer - Lap Joints



Optimum at: (Angle=35, Volts=345, Pulse=2.5, Focus=20)


Main Effects Plot for Break Strength - NiWire Joints
Angle of Attack
Volts
Pulse Length
Focus
Break Strength (lbs)
27.8
26.6
25.4
24.2
23.0
30
45
60
310
330
350
1.5
2.0
2.5
16
18
20

Interaction Plots for Break Strength - NiWire Joints



Response Surface Regression for Break Strength - NiWire Joints

The analysis was done using coded units.

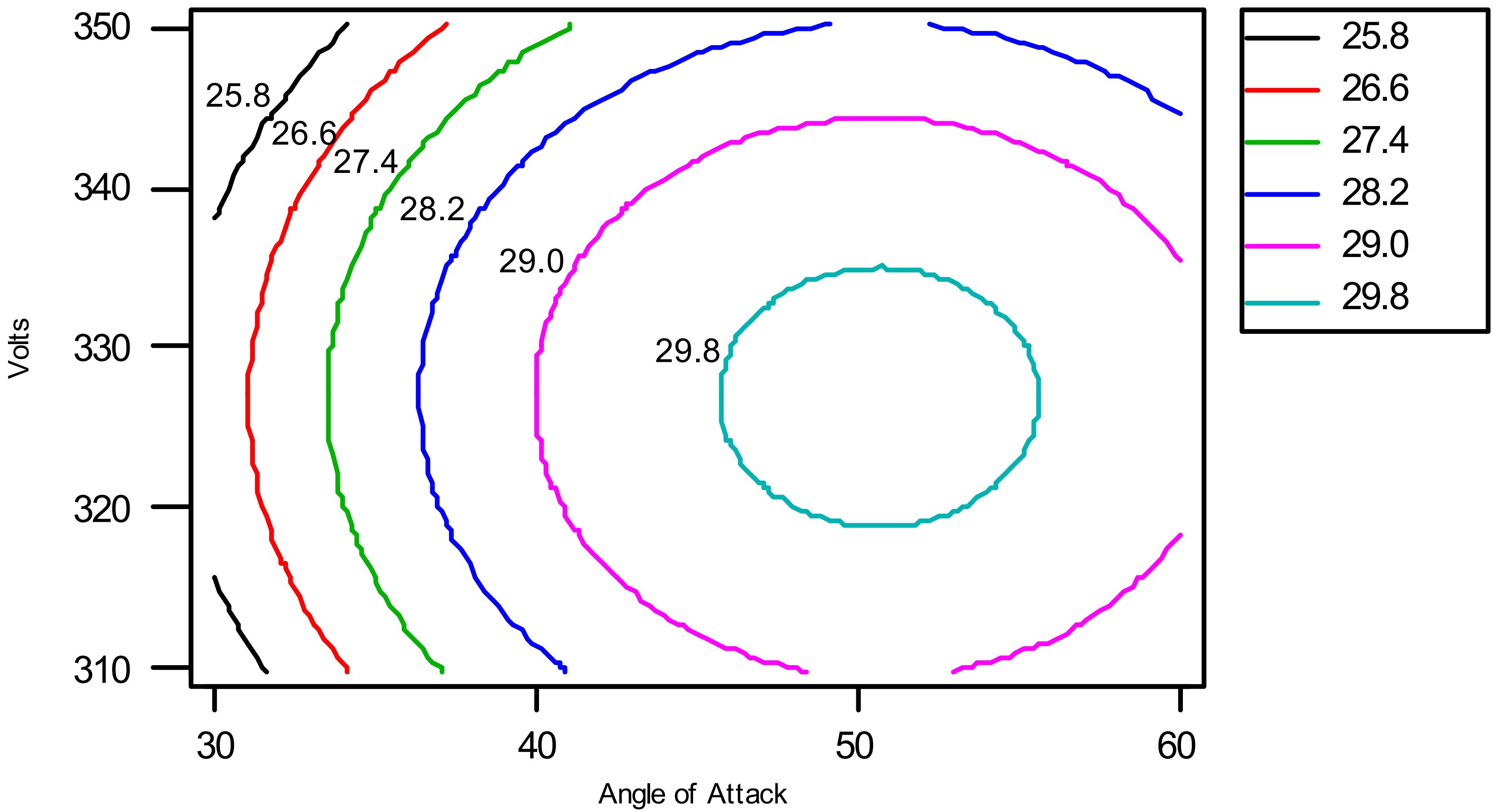
Estimated Regression Coefficients for Break Strength

Term	**Coef**	**StDev**	**T**	**P**
Constant	29.554	0.7813	37.828	0.000
Angle of Attack	1.509	0.4592	3.286	0.009
Volts	-0.412	0.4525	-0.912	0.386
Pulse Length	-0.142	0.5109	-0.278	0.787
Focus	-0.750	0.5211	-1.440	0.184
Angle*Angle	-2.004	1.0204	-1.964	0.081
Volts*Volts	-1.354	1.0204	-1.327	0.217
Pulse*Pulse	-2.304	1.0204	-2.258	0.050
Focus*Focus	-0.904	1.0204	-0.886	0.399
Angle*Pulse	-1.100	0.5018	-2.193	0.056
Pulse*Focus	1.672	0.5569	3.001	0.015

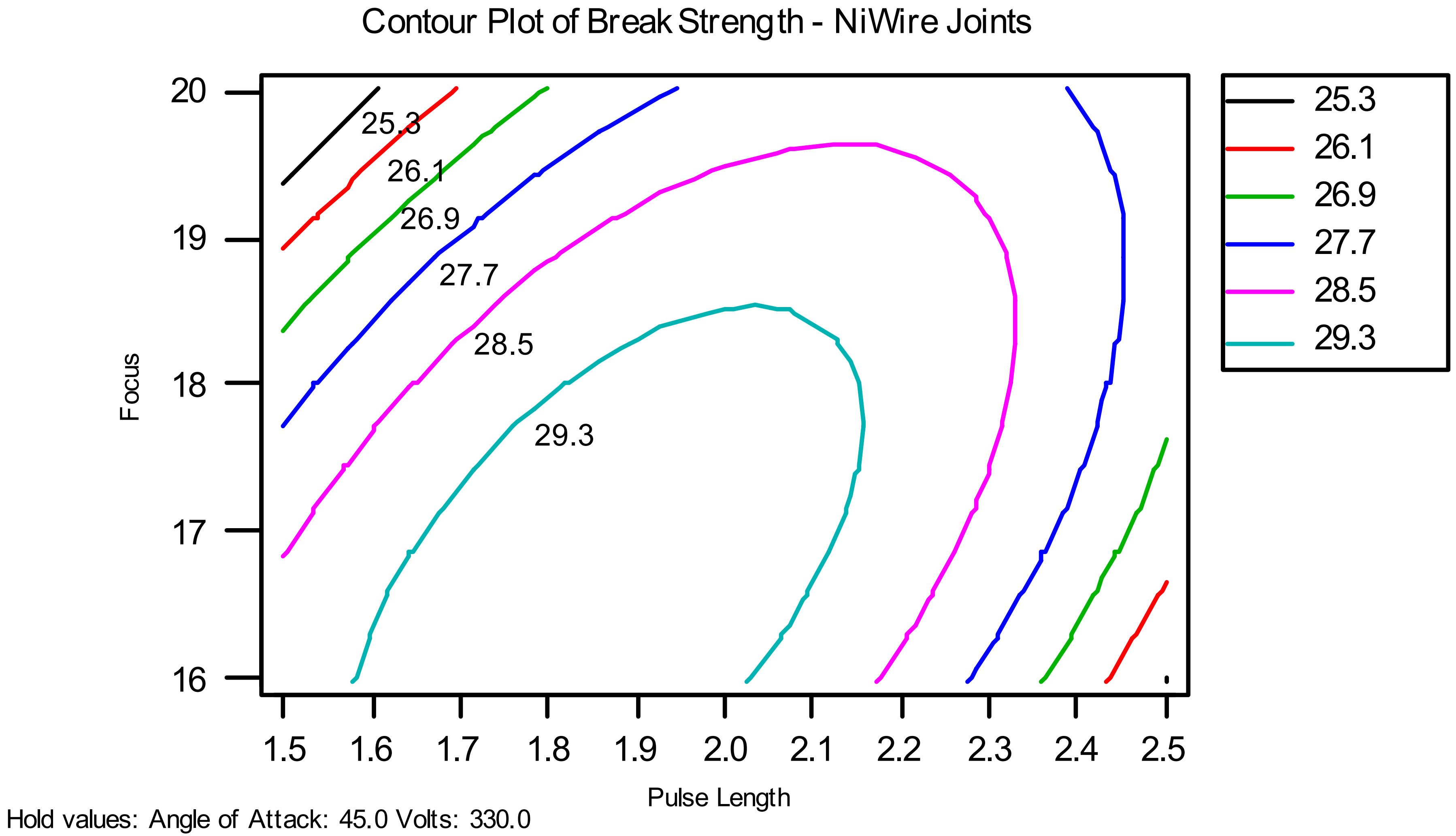
S = 1.608   R-Sq = 86.7%

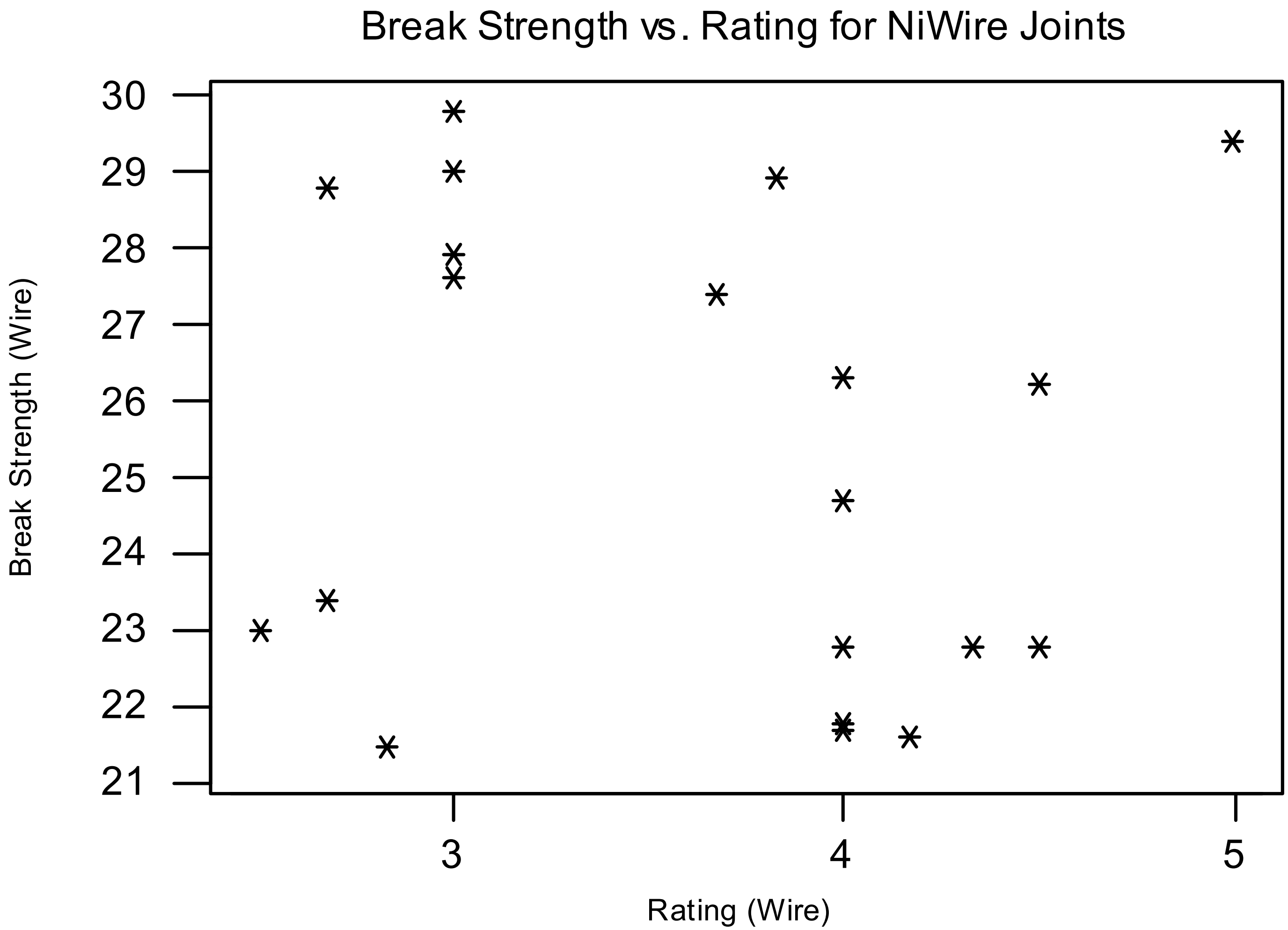
Standard Deviation of Fits = 1.2

Contour Plot of Break Strength - NiWire Joints

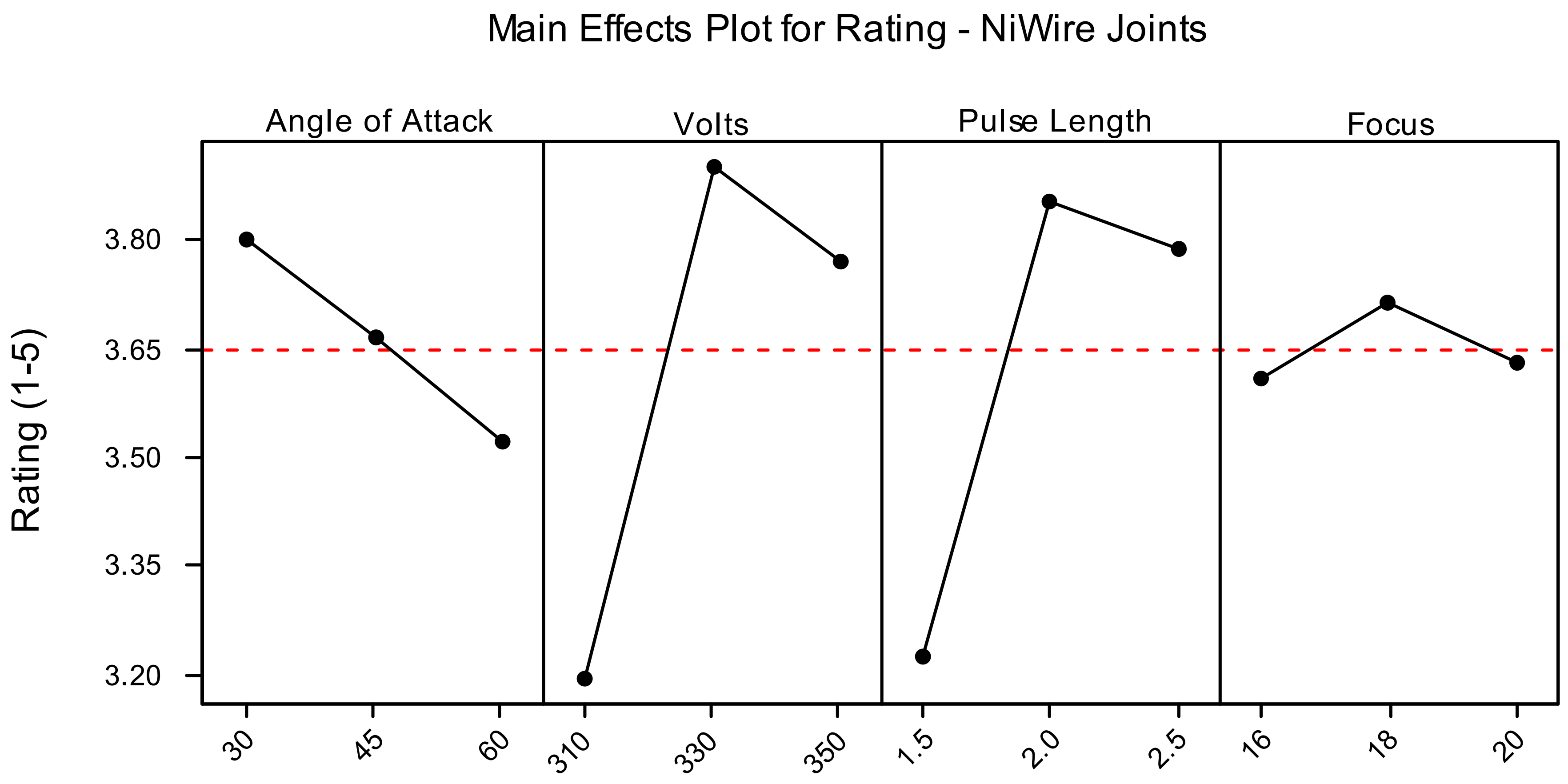


Hold values: Pulse Length: 2.0 Focus: 17.0


Contour Plot of Break Strength - NiWire Joints
Focus
Pulse Length
25.3
26.1
26.9
27.7
28.5
29.3
Hold values: Angle of Attack: 45.0 Volts: 330.0

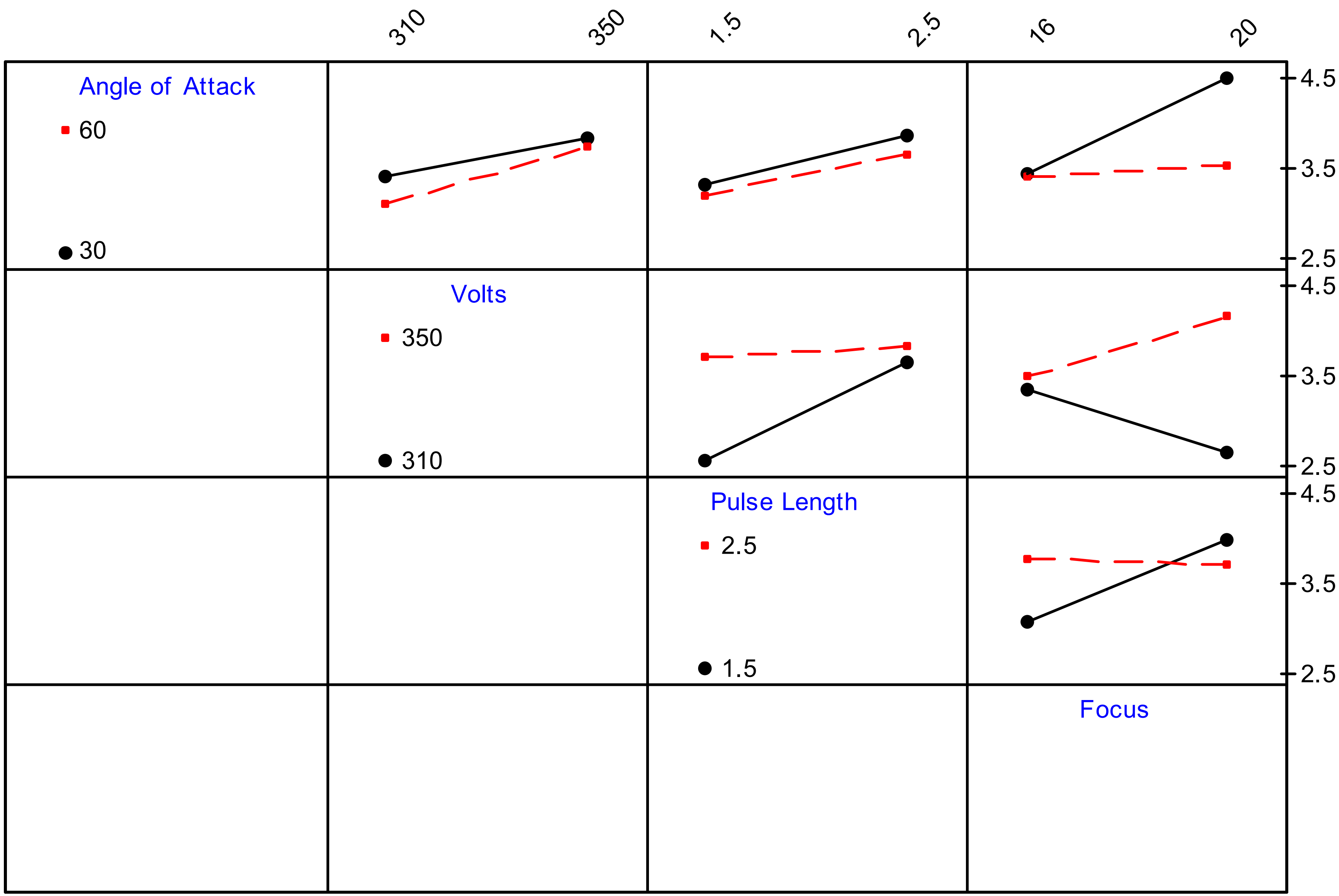


Break Strength vs. Rating for NiWire Joints
Break Strength (Wire)
30
29
28
27
26
25
24
23
22
21
3
4
5
Rating (Wire)



Main Effects Plot for Rating - NiWire Joints
Angle of Attack
Volts
Pulse Length
Focus
Rating (1-5)
3.80
3.65
3.50
3.35
3.20
30
45
60
310
330
350
1.5
2.0
2.5
16
18
20

Interaction Plots for Rating - NiWire Joints



A23

Response Surface Regression for Rating - NiWire Joints

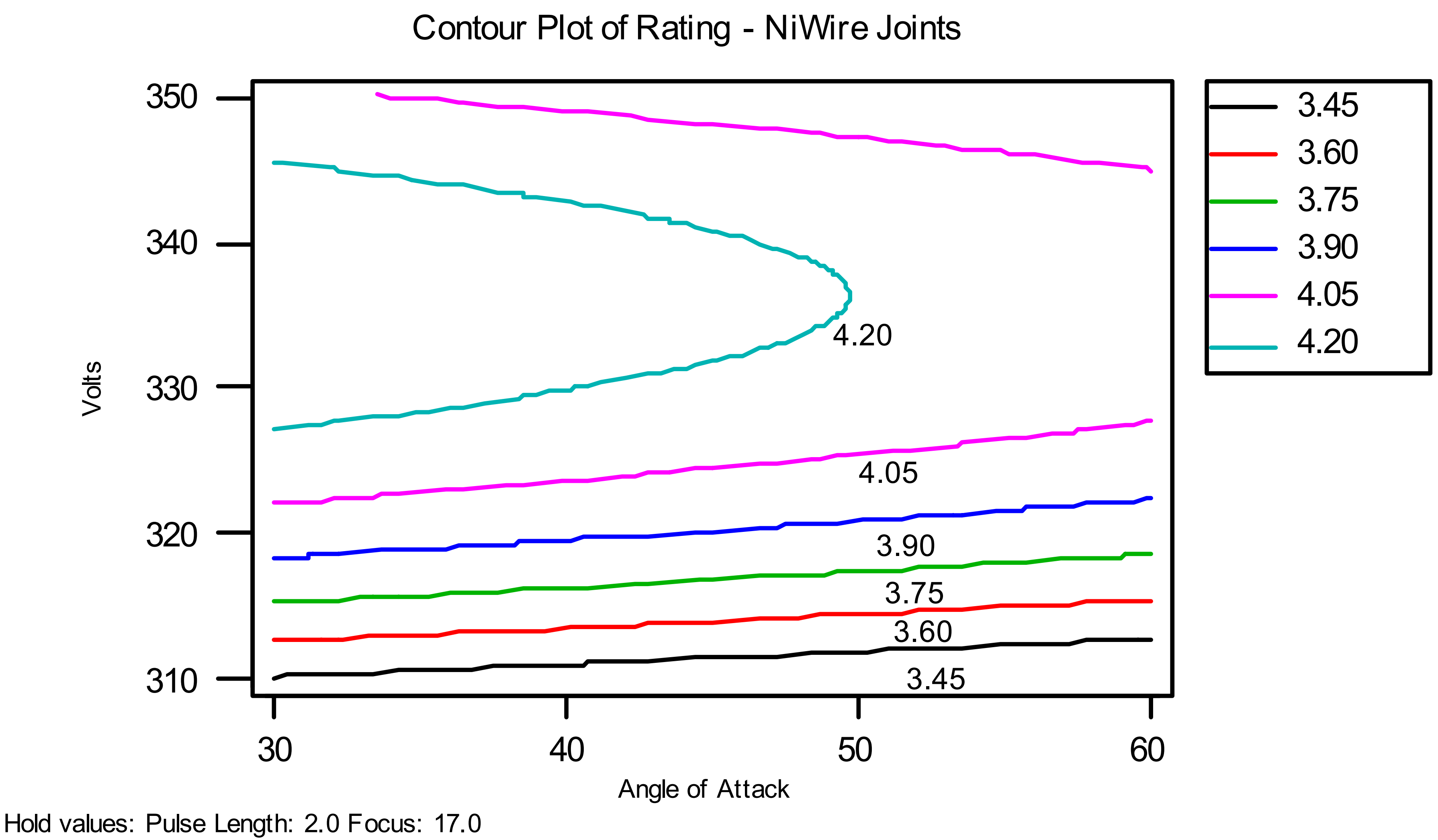
The analysis was done using coded units.

Estimated Regression Coefficients for Rating

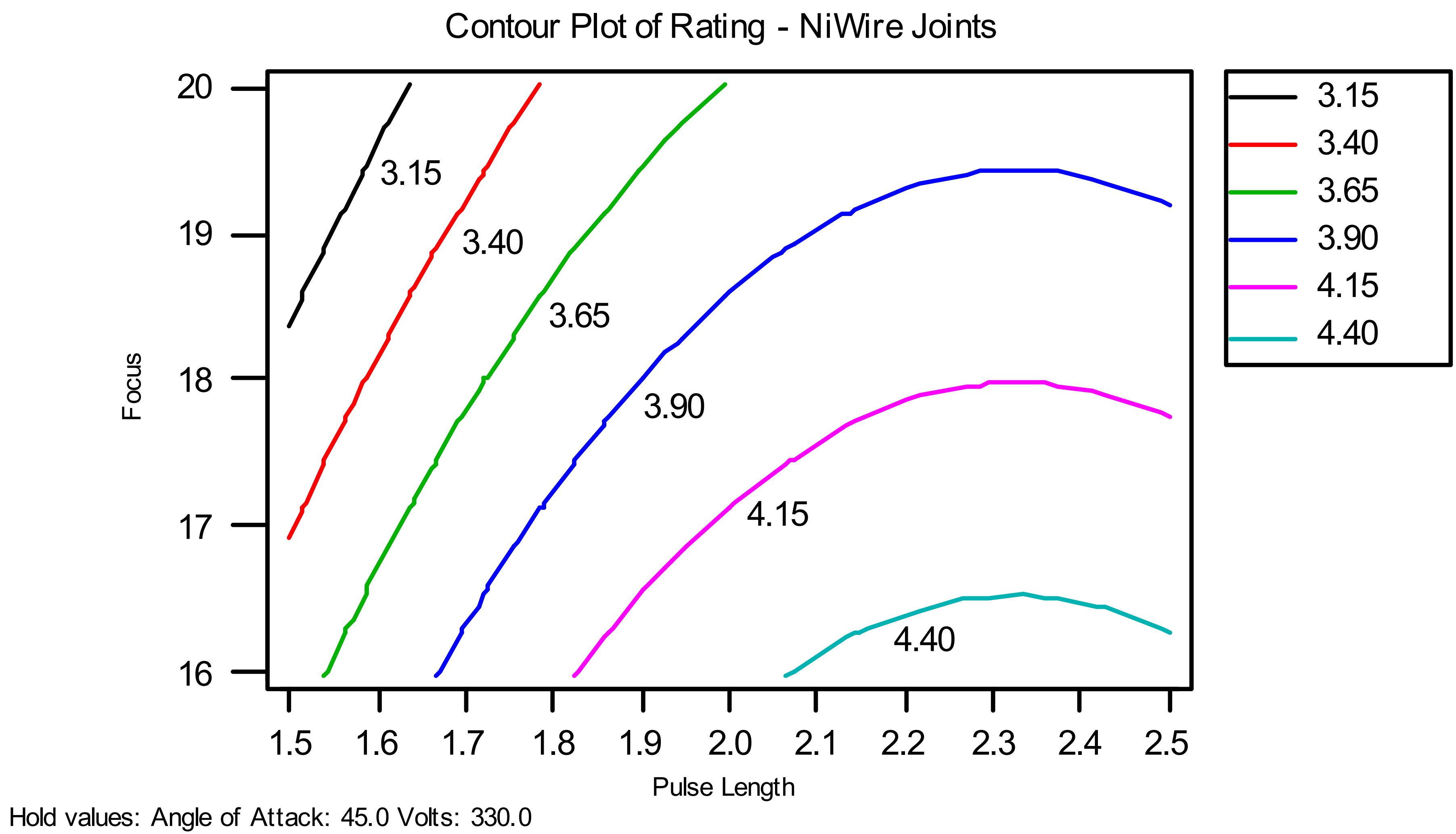
Term	Coef	StDev	T	P
Constant	4.0019	0.2100	19.058	0.000
Angle of Attack	-0.0806	0.1430	-0.564	0.583
Volts	0.6125	0.1609	3.807	0.002
Pulse Length	0.4447	0.1450	3.067	0.010
Focus	-0.3455	0.1633	-2.116	0.056
Volts*Volts	-0.5066	0.2928	-1.730	0.109
Pulse*Pulse	-0.3416	0.2928	-1.166	0.266
Volts*Pulse	-0.4263	0.1589	-2.683	0.020
Volts*Focus	0.5847	0.1753	3.335	0.006

S = 0.5096   R-Sq = 70.0%

Standard Deviation of Fits = .35

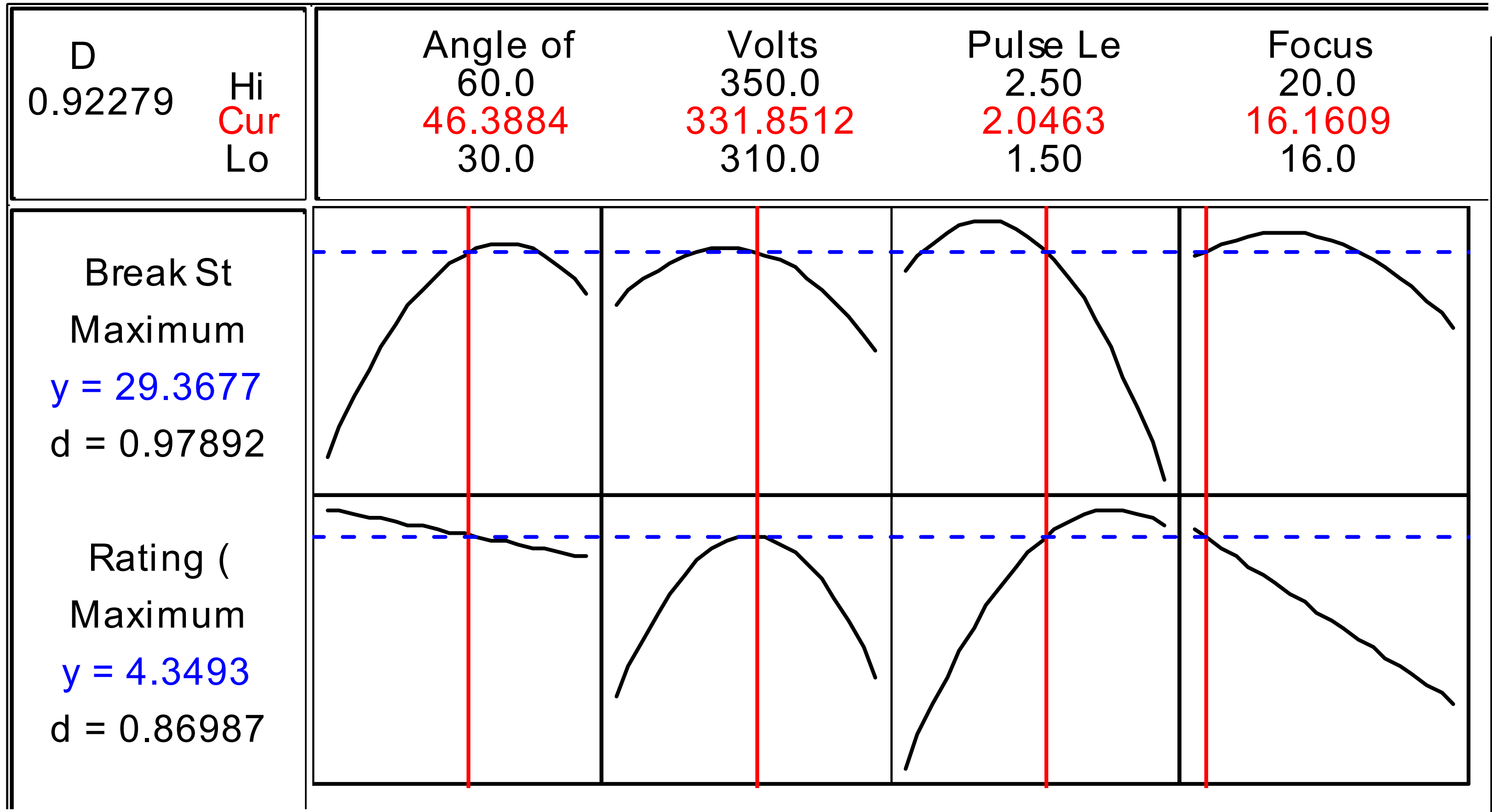


Contour Plot of Rating - NiWire Joints
350
340
330
320
310
Volts
30
40
50
60
Angle of Attack
4.20
4.05
3.90
3.75
3.60
3.45
3.45
3.60
3.75
3.90
4.05
4.20
Hold values: Pulse Length: 2.0 Focus: 17.0

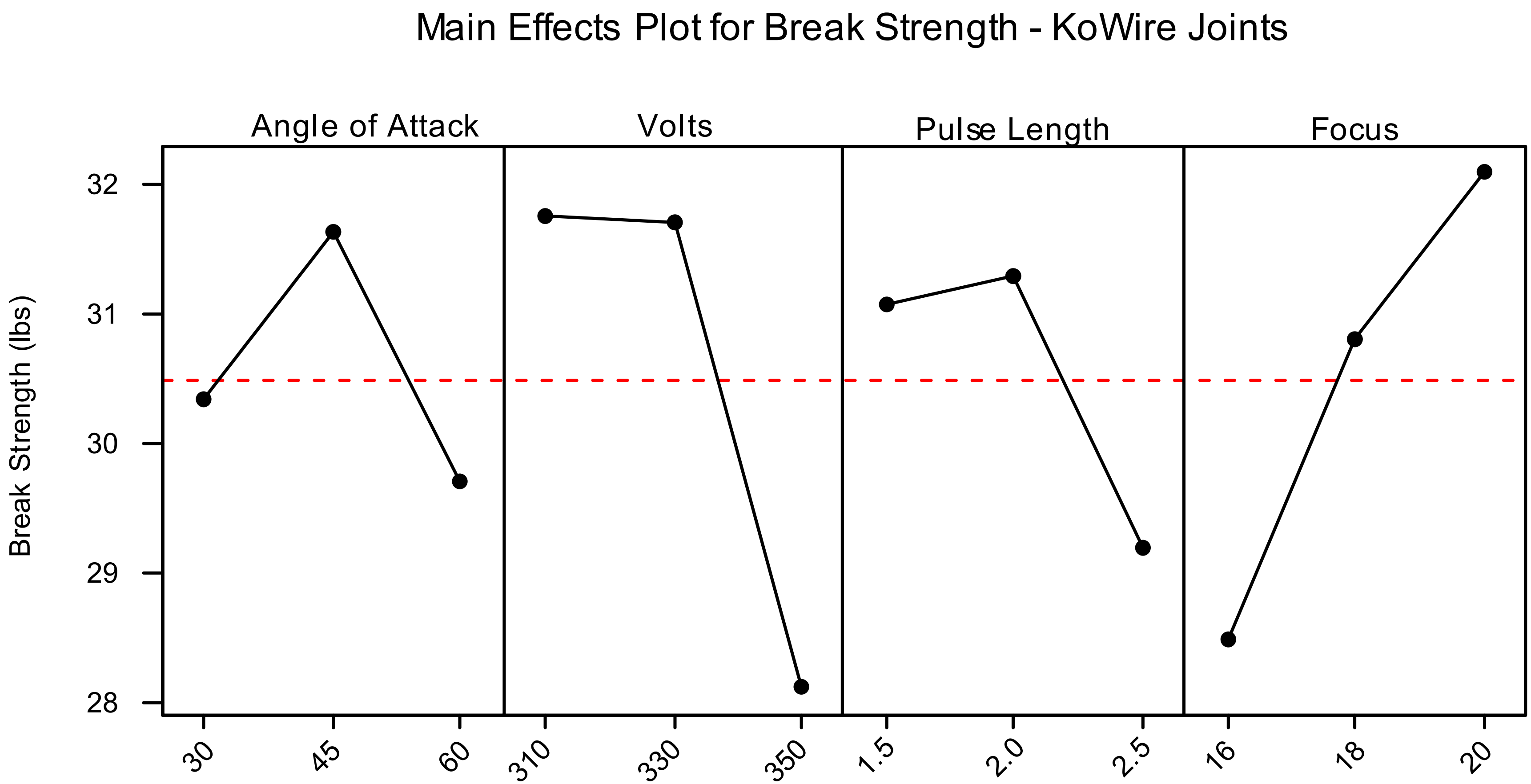


Contour Plot of Rating - NiWire Joints
3.15
3.40
3.65
3.90
4.15
4.40
20
19
18
17
16
Focus
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
Pulse Length
Hold values: Angle of Attack: 45.0 Volts: 330.0

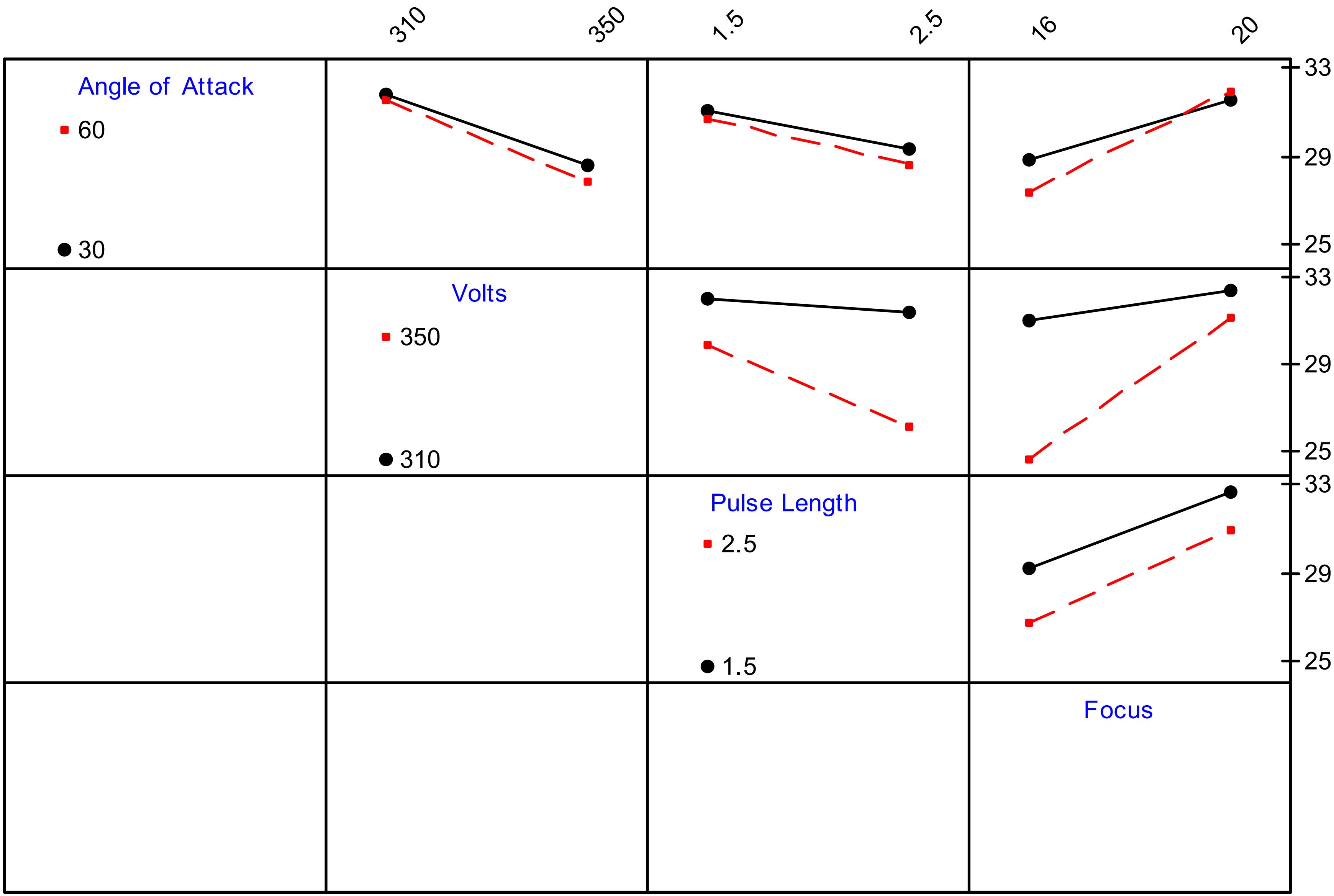
Multiple Response Optimizer - NiWire Joints



Optimum at: (Angle=46, Volts=332, Pulse=2.0, Focus=16)


Main Effects Plot for Break Strength - KoWire Joints
Angle of Attack
Volts
Pulse Length
Focus
Break Strength (lbs)
32
31
30
29
28
30
45
60
310
330
350
1.5
2.0
2.5
16
18
20

Interaction Plots for Break Strength - KoWire Joints



Response Surface Regression for Break Strength - KoWire Joints

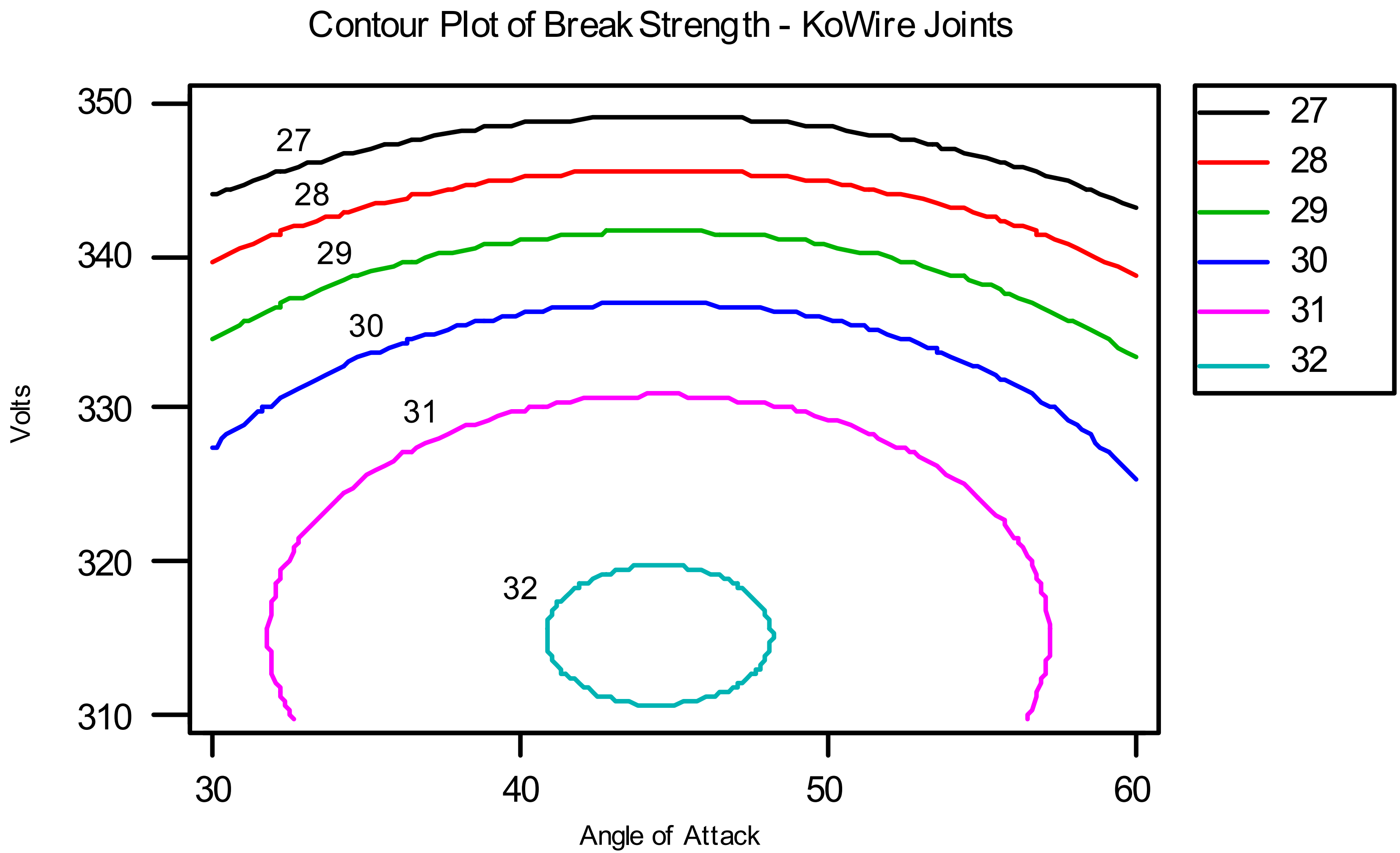
The analysis was done using coded units.

Estimated Regression Coefficients for Break Strength

Term	Coef	StDev	T	P
Constant	31.773	0.4154	76.492	0.000
Angle of Attack	-0.103	0.2348	-0.438	0.664
Volts	-1.983	0.2348	-8.448	0.000
Pulse Length	-1.119	0.2348	-4.768	0.000
Focus	1.964	0.2348	8.365	0.000
Angle*Angle	-1.527	0.5905	-2.586	0.014
Volts*Volts	-1.802	0.5905	-3.052	0.004
Focus*Focus	1.323	0.5905	2.240	0.031
Volts*Pulse Length	-0.881	0.2495	-3.531	0.001
Volts*Focus	1.319	0.2495	5.285	0.000

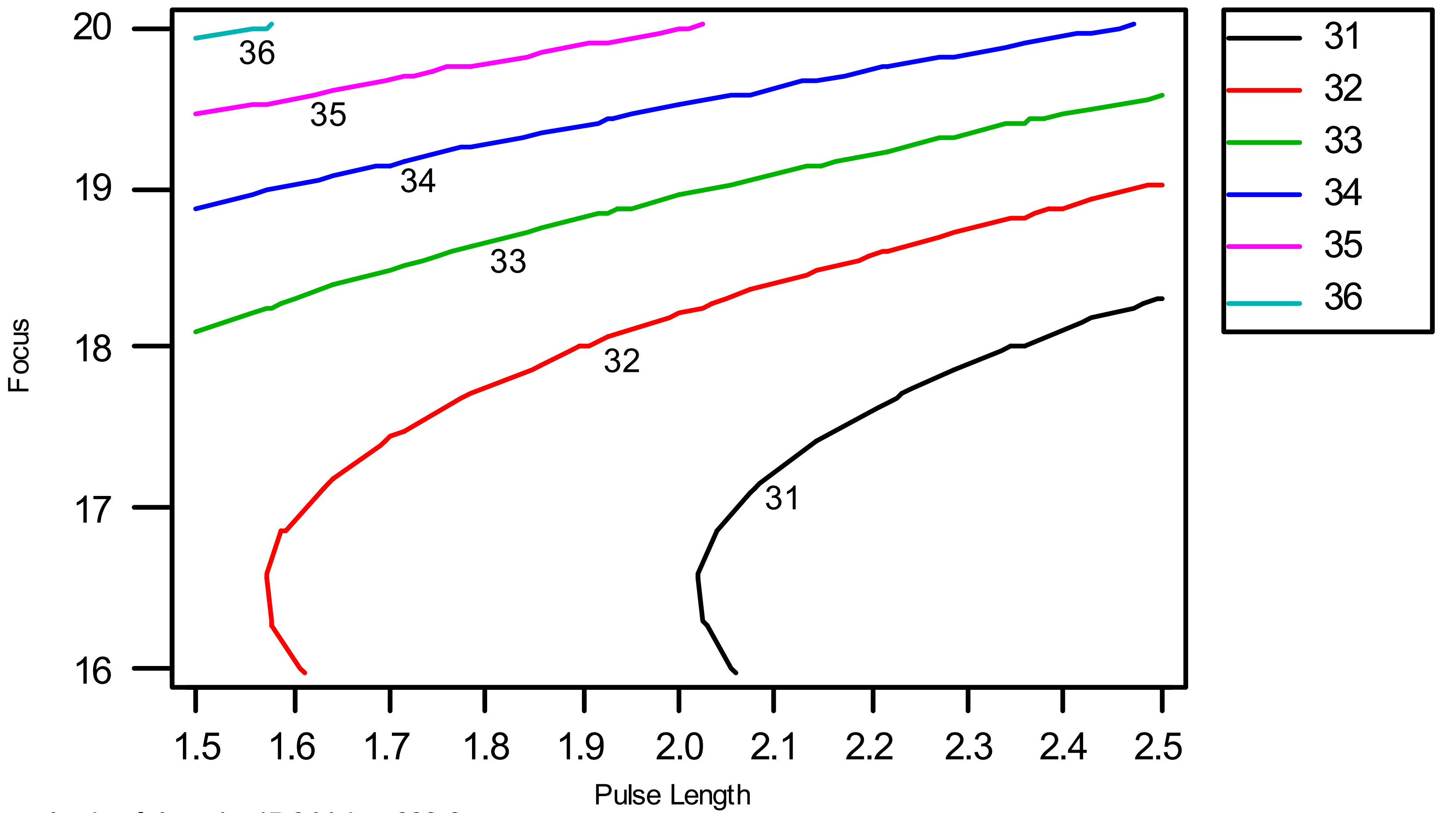
S = 1.385   R-Sq = 84.2%

Standard Deviation of Fits = .70

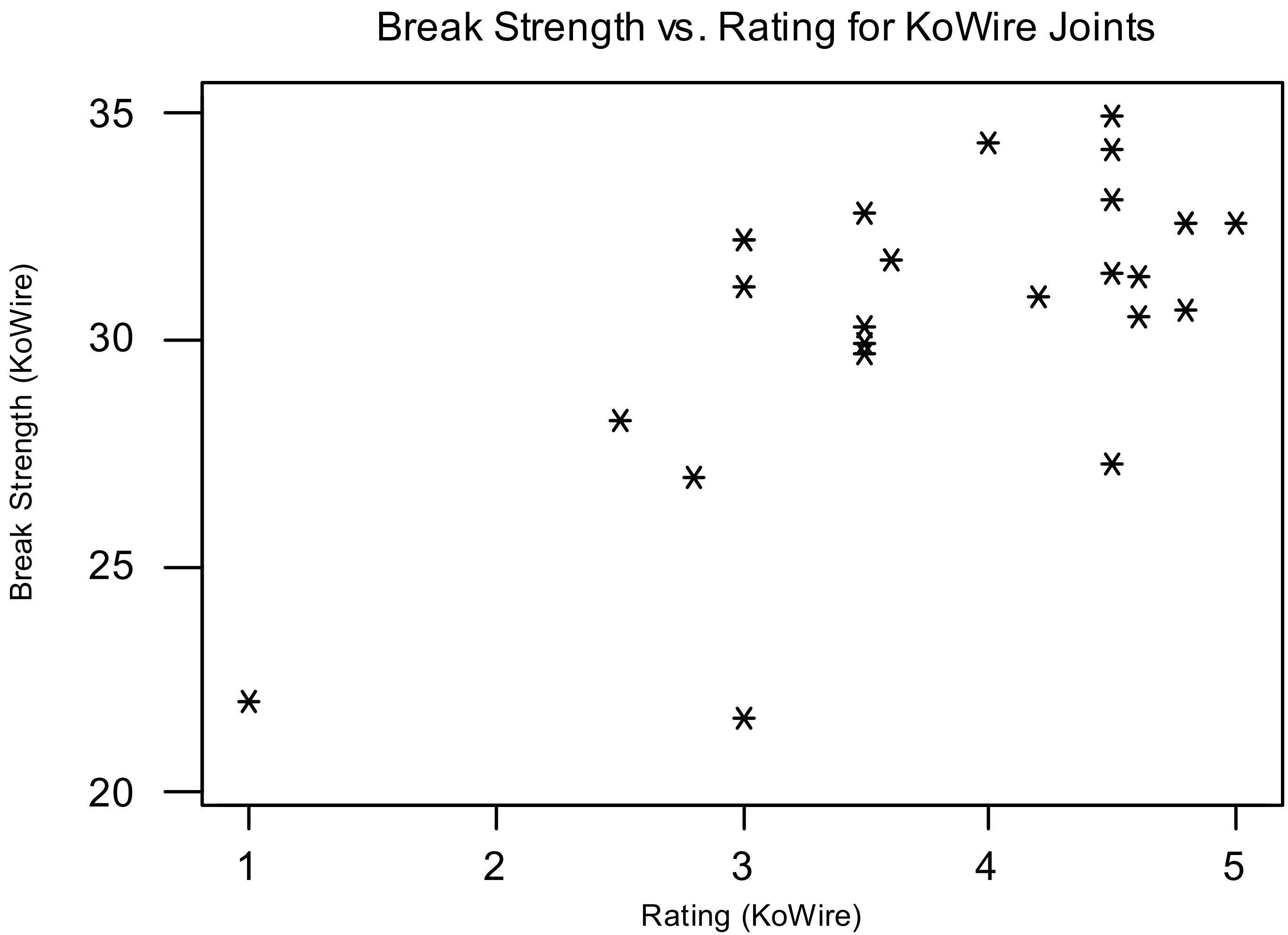


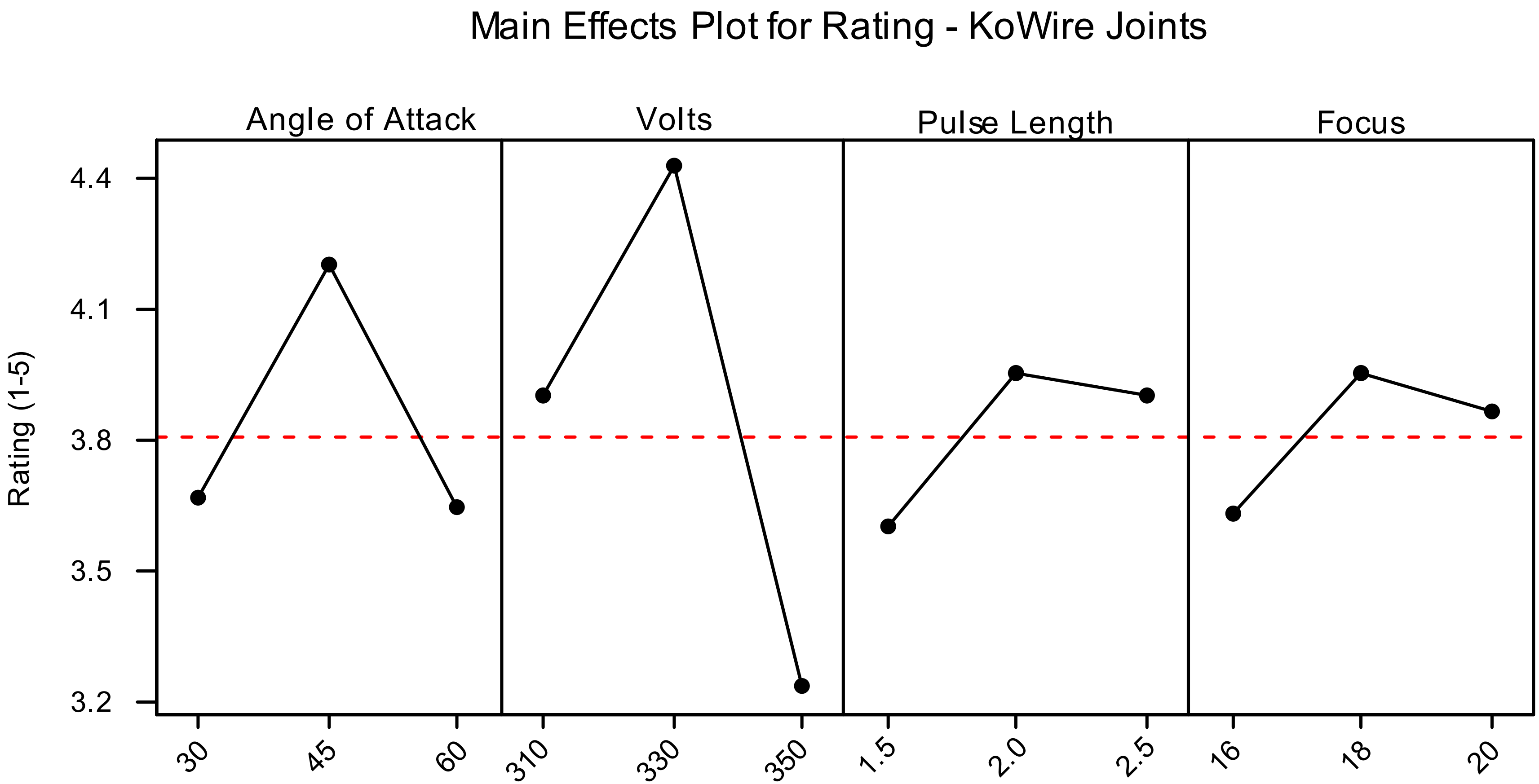
Hold values: Pulse Length: 2.0 Focus: 17.0

Contour Plot of Break Strength - KoWire Joint



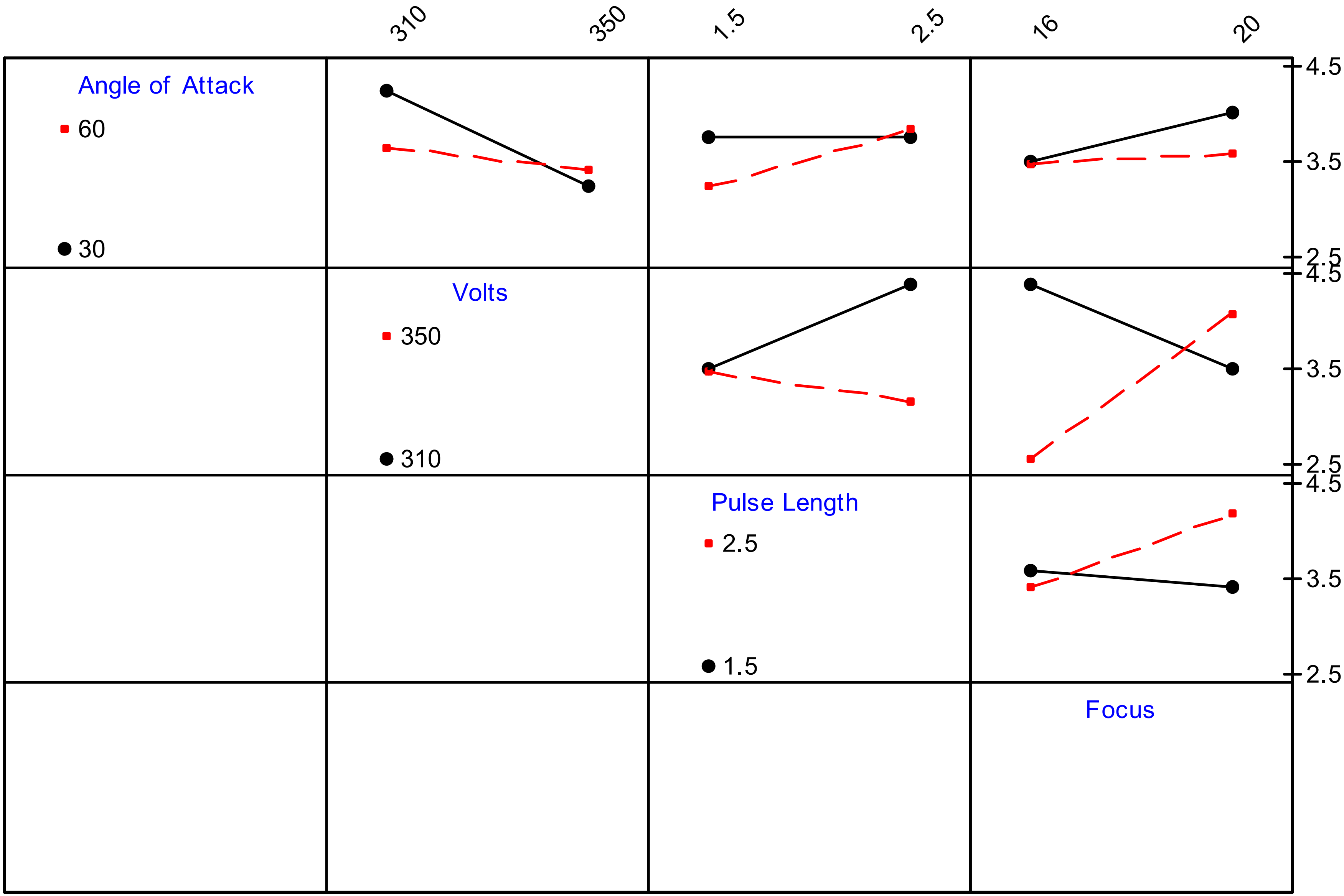
Hold values: Angle of Attack: 45.0 Volts: 330.0


Break Strength vs. Rating for KoWire Joints
35
30
25
20
Break Strength (KoWire)
1
2
3
4
5
Rating (KoWire)



Main Effects Plot for Rating - KoWire Joints
Angle of Attack
Volts
Pulse Length
Focus
Rating (1-5)
4.4
4.1
3.8
3.5
3.2
30
45
60
310
330
350
1.5
2.0
2.5
16
18
20

Interaction Plots for Rating - KoWire Joints



A35

Response Surface Regression for Rating - KoWire Joints

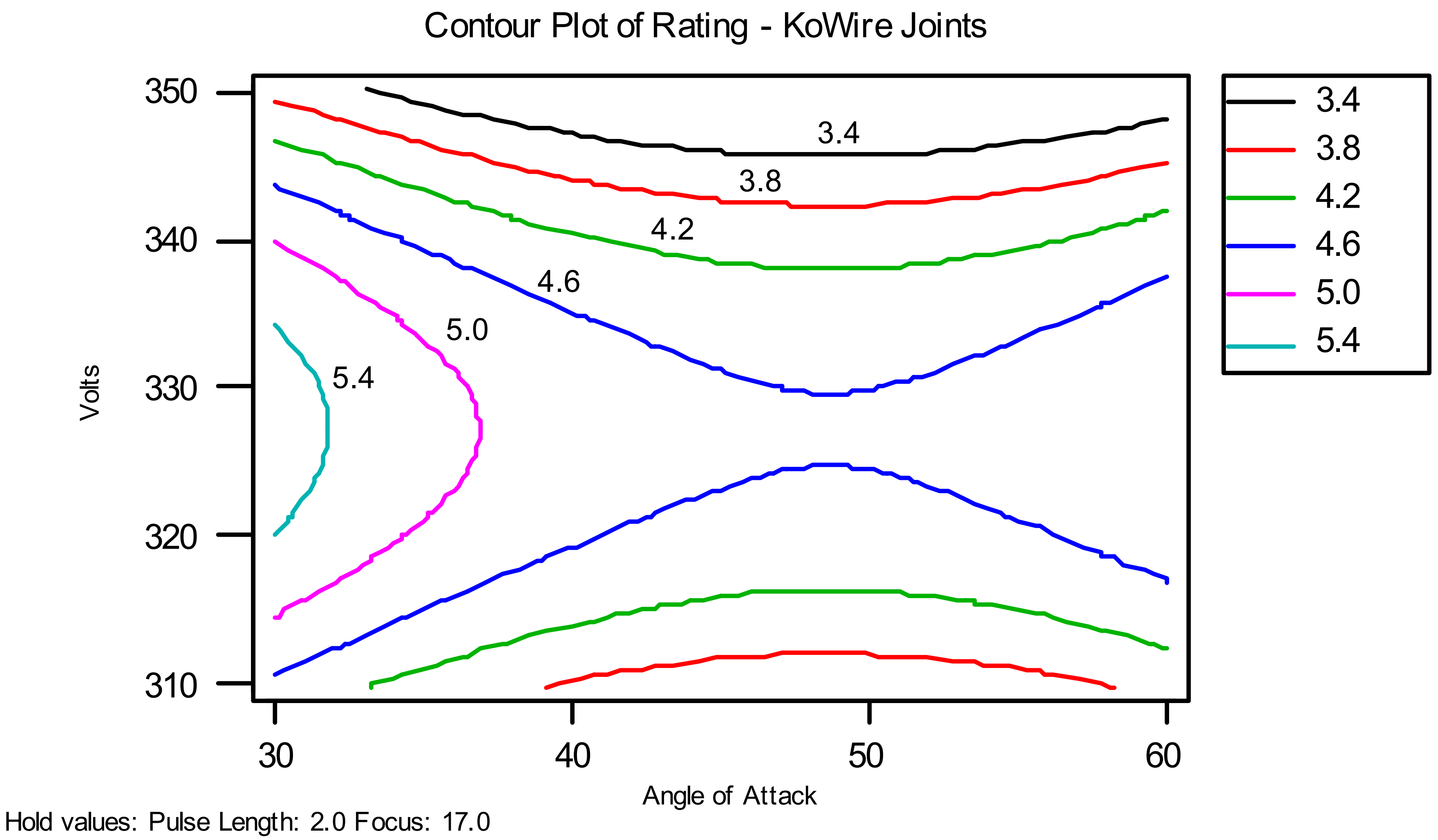
The analysis was done using coded units.

Estimated Regression Coefficients for Rating

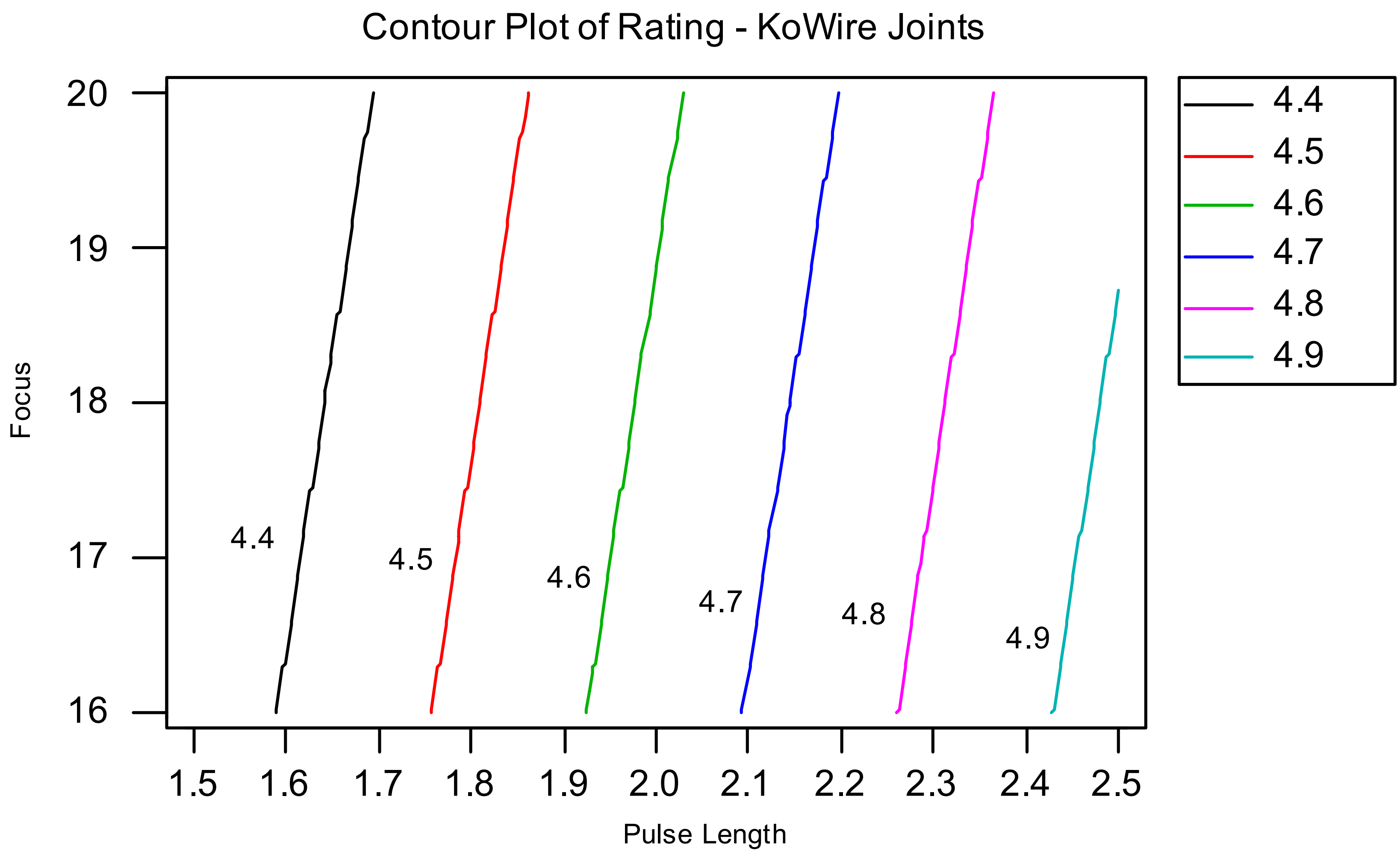
Term	**Coef**	**StDev**	**T**	**P**
Constant	4.614	0.11474	40.210	0.000
Angle of Attack	-0.299	0.07041	-4.251	0.001
Volts	-0.186	0.06707	-2.769	0.015
Pulse Length	0.298	0.06707	4.438	0.001
Focus	-0.031	0.06707	-0.462	0.652
Angle*Angle	0.617	0.17106	3.607	0.003
Volts*Volts	-1.448	0.17861	-8.107	0.000
Volts*Pulse	-0.134	0.07152	-1.873	0.082
Volts*Focus	0.434	0.07152	6.067	0.000

S = 0.2719   R-Sq = 91.9%

Standard Deviation of Fits = .20

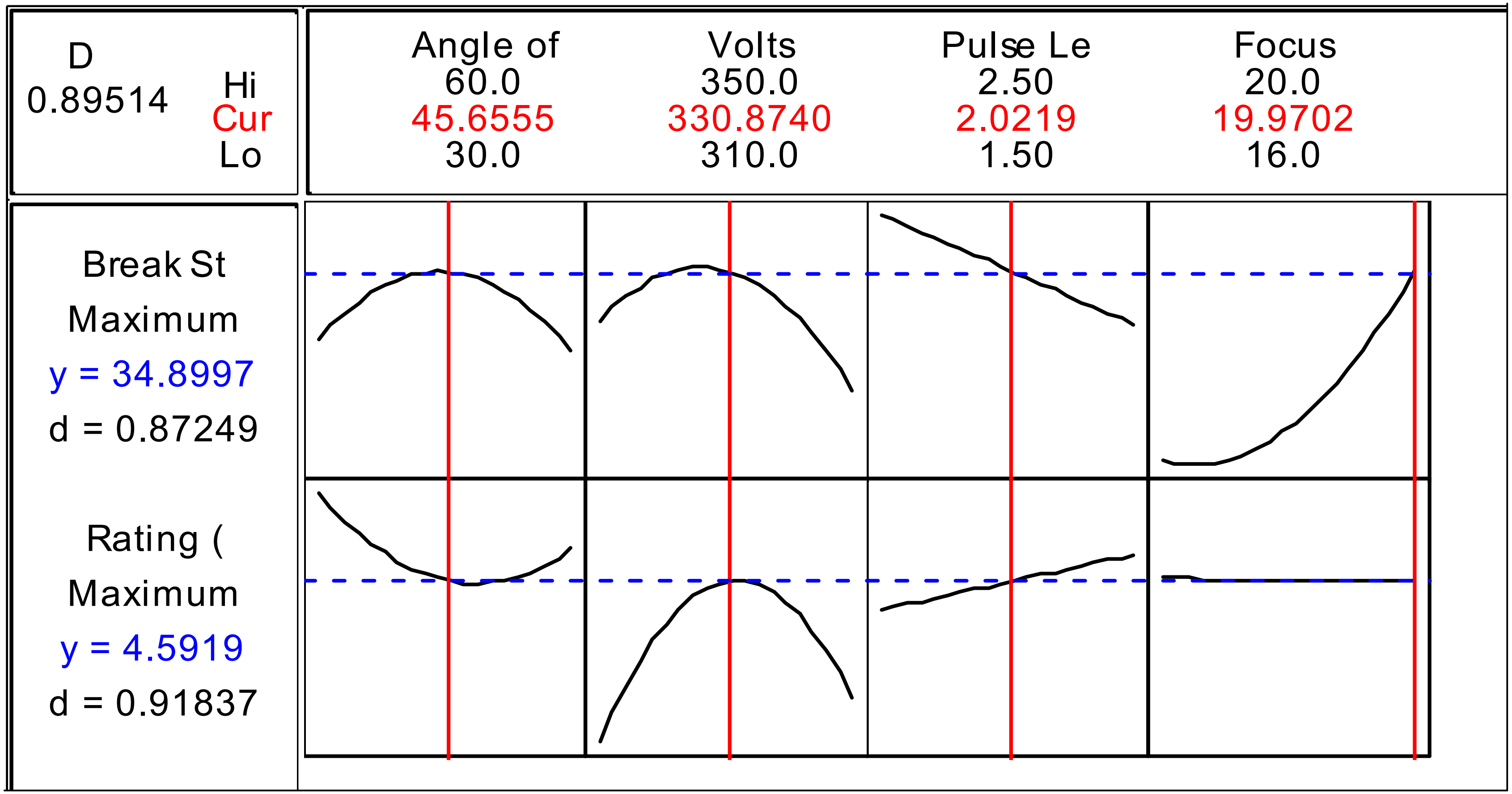


Contour Plot of Rating - KoWire Joints
350
340
330
320
310
Volts
30
40
50
60
Angle of Attack
3.4
3.8
4.2
4.6
5.0
5.4
Hold values: Pulse Length: 2.0 Focus: 17.0



Hold values: Angle of Attack: 45.0 Volts: 330.0

Multiple Response Optimizer - KoWire Joints



Optimum at: (Angle=45, Volts=330, Pulse=2.0, Focus=20)

Operating Windows for Each Process Factor and Each Weld Type

Weld Type	Angle of Attack	Volts	Pulse Length	Focus
Lap Joints	30-50 Degrees	330-350 V	1.9-2.5 ms	16-20
NiWire Joints	40-60 Degrees	320-350 V	1.8-2.4 ms	16-20
KoWire Joints	35-55 Degrees	310-340 V	1.5-2.4 ms	16-20

Multiple Response Optimization

Optimizing over all six responses (3 weld types, 2 responses each) simultaneously leads to a solution of:

(Angle of Attack= 35, Volts= 340, Pulse Length= 2.4, Focus= 19.5)

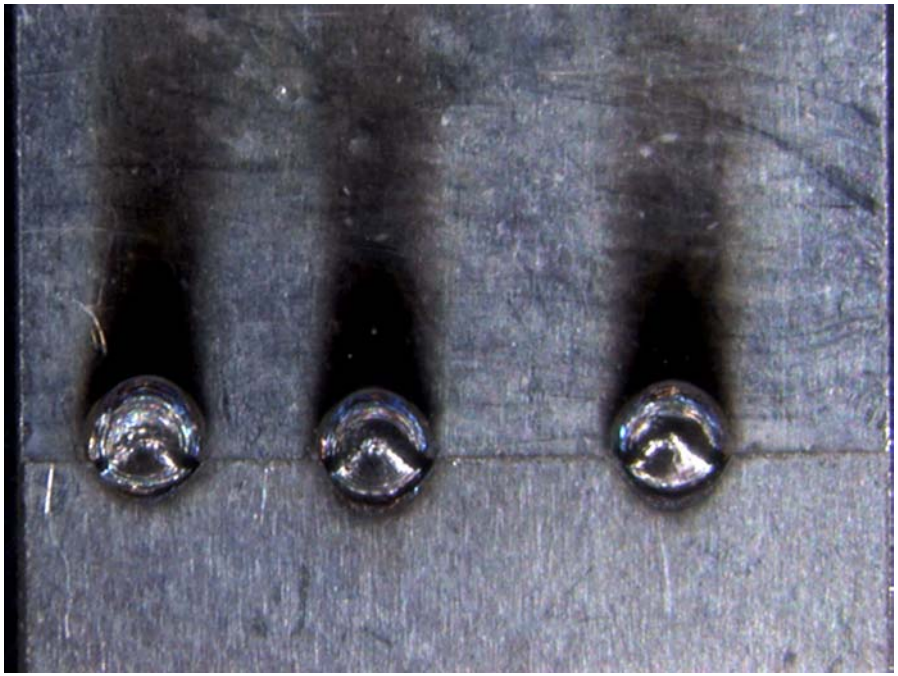
If the importance rating for the Lap Weld is twice the rating for the other two weld types the solution is:

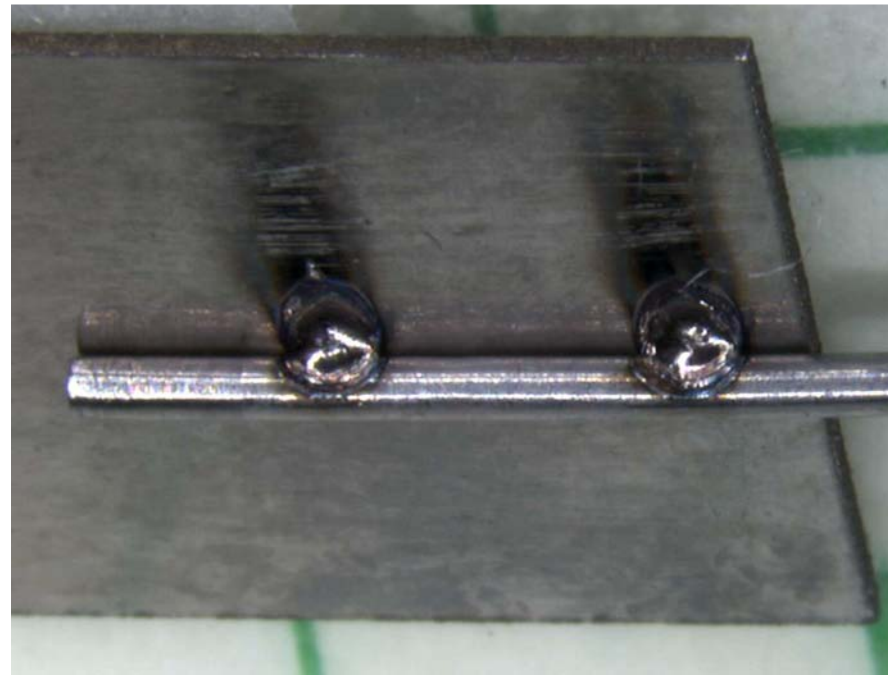
(Angle of Attack= 30, Volts= 340, Pulse Length= 2.4, Focus= 19.5)

MC4368A/MC4531 Laser Welding
Metallurgical Evaluations

- The following photographs are representative samples taken from the various baseline processing angle (PA) studies, calibration studies, gap experimentation & Design of Experiments.

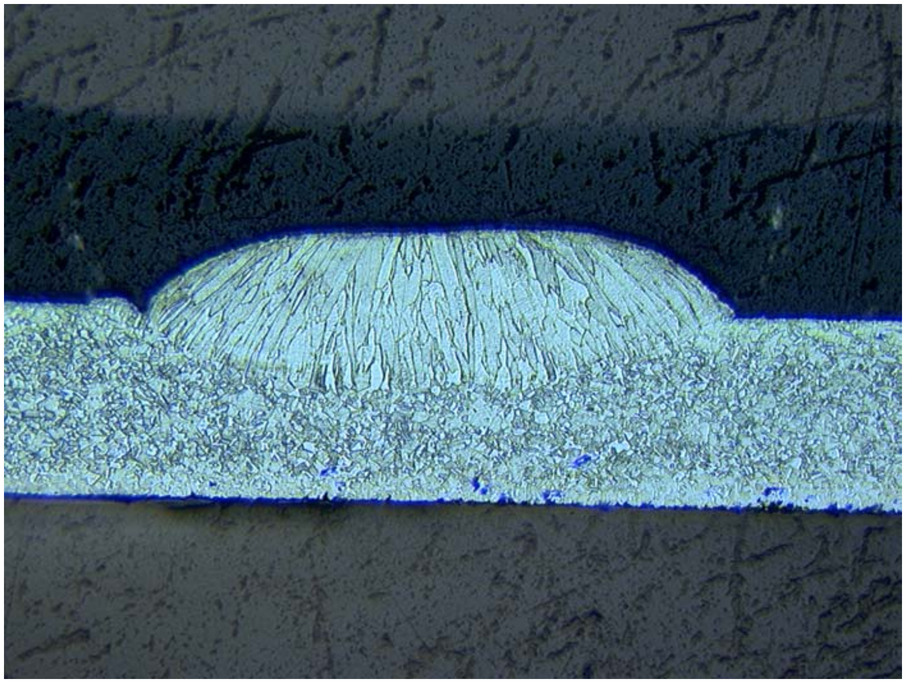
MC4368A/MC4531 Laser Welding
Metallurgical Evaluations

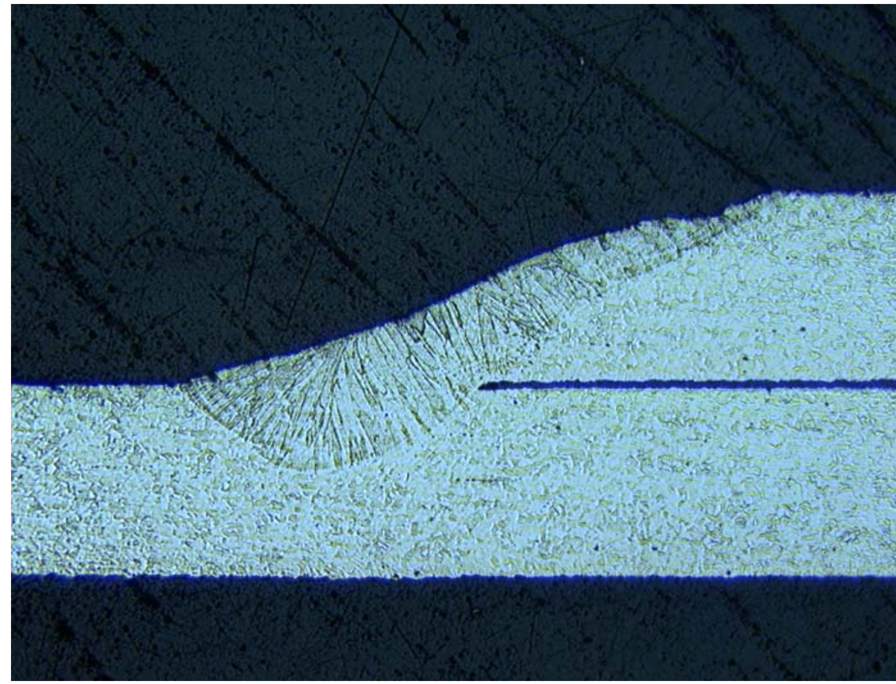




These photographs show the two types of joints that were performed in the Design of Experiments Study. The left photo shows the .010" Kovar to .010" Kovar sheet lap joint; while, the right photo shows the Kovar & Ni .0215" diameter wire to .010" Kovar sheet flare beveled groove joint.

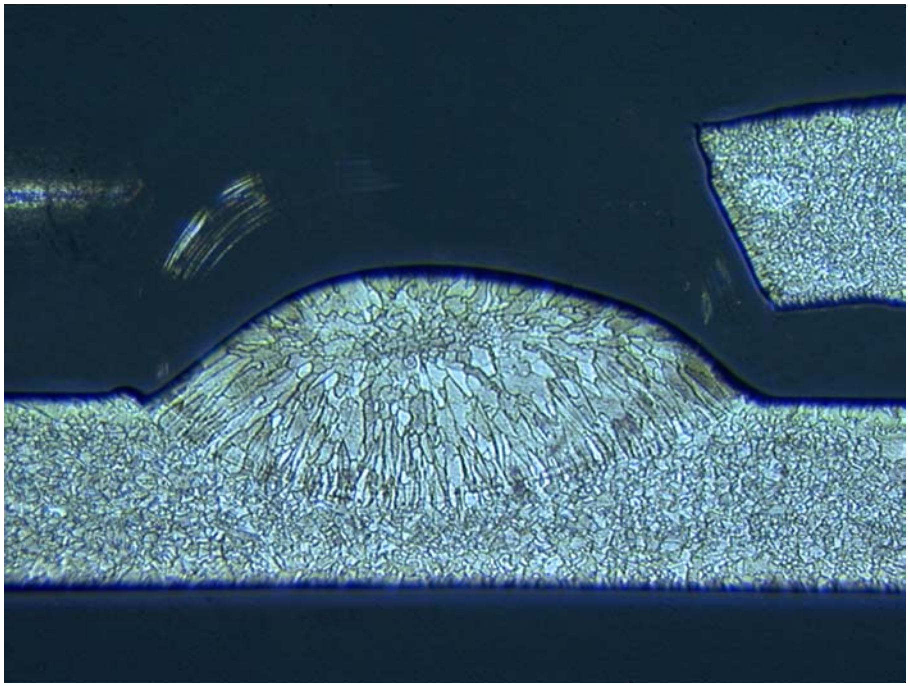
MC4368A/MC4531 Laser Welding
Metallurgical Evaluations

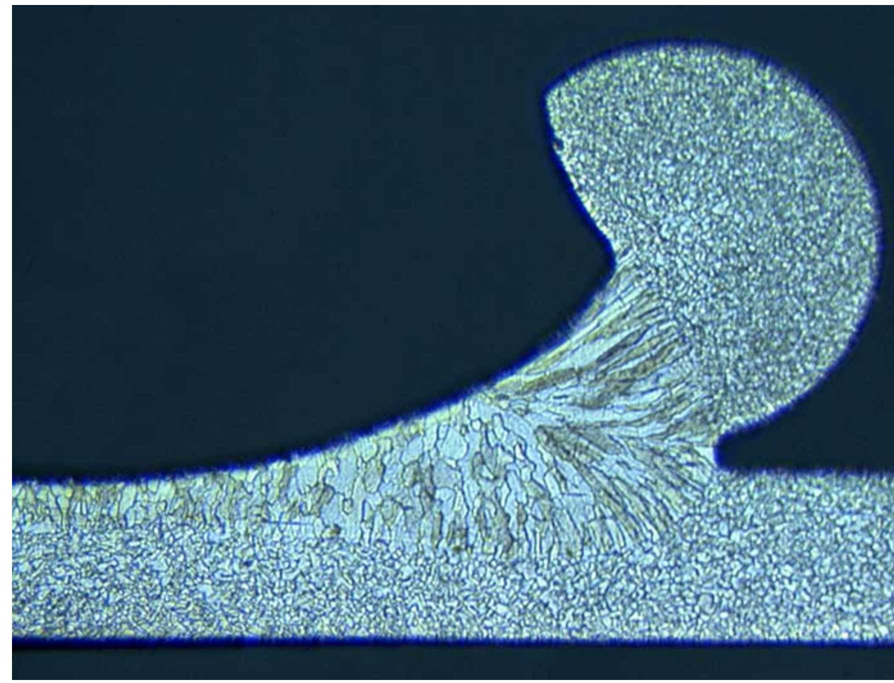




These two photo micro-graphs are cross-sections of the .010" Kovar sheet lap joints. The left photo shows a transverse view of the weld bead, while the right photo shows a longitudinal view. This metallurgical analysis shows no anomalies in the microstructure.

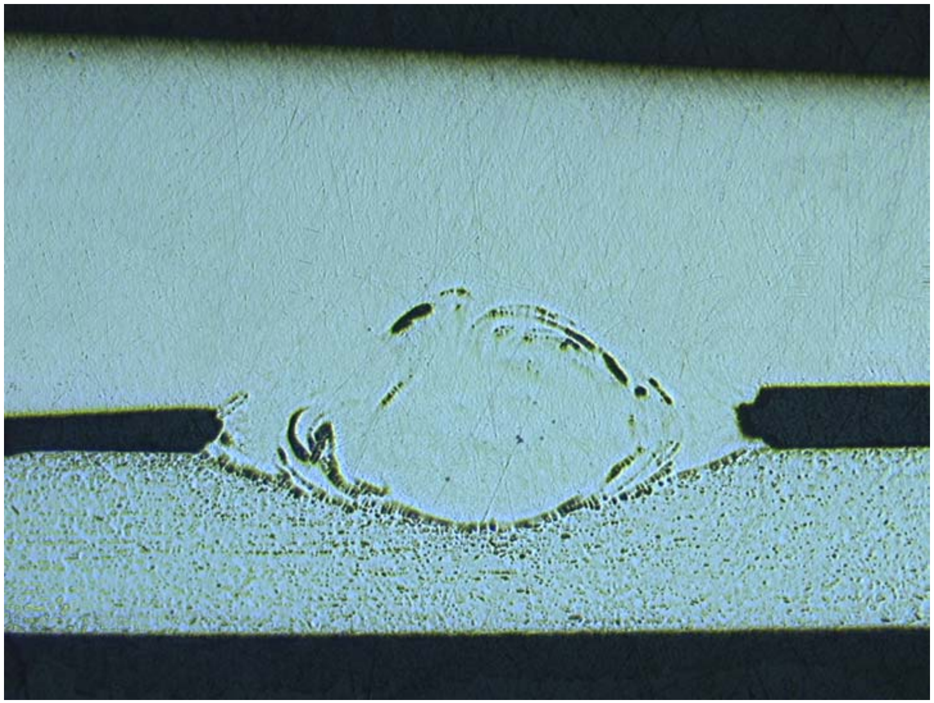
MC4368A/MC4531 Laser Welding Metallurgical Evaluations

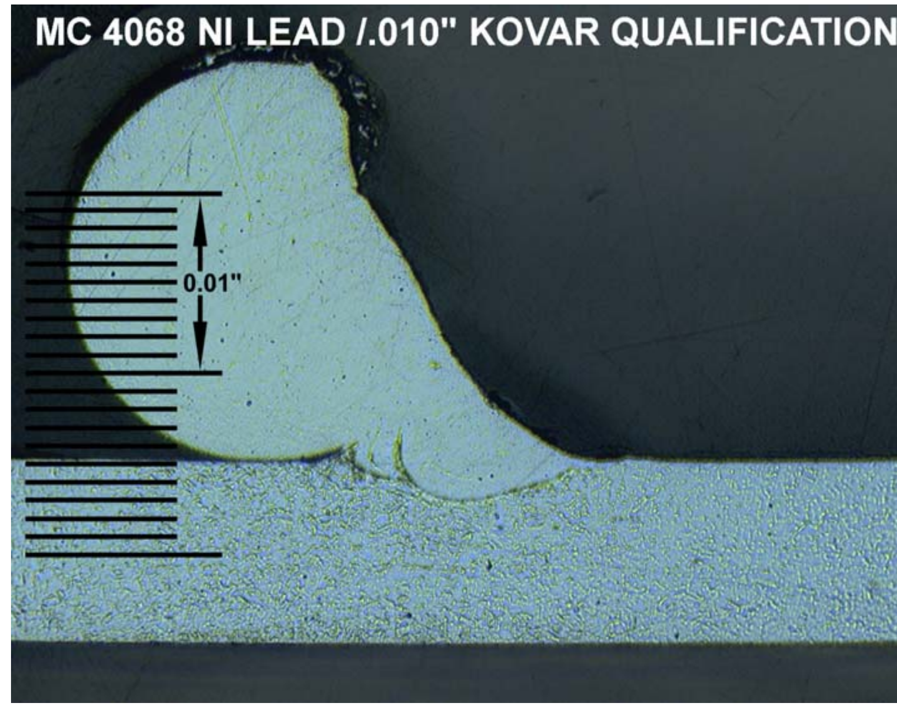




These two photo micro-graphs are cross-sections of the .0215” Ø Kovar wire to the .010” Kovar sheet flare bevel groove joint. The left photo shows a longitudinal view of the weld bead, while the right photo shows a transverse view. This metallurgical analysis, also, shows no anomalies in the microstructure.

MC4368A/MC4531 Laser Welding
Metallurgical Evaluations





These two photo micro-graphs are cross-sections of the .0215" Ø Ni wire to the .010" Kovar sheet flare bevel groove joint. The left photo shows a longitudinal view of the weld bead, while the right photo shows a transverse view. This metallurgical analysis, also, shows no anomalies in the microstructure.

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This photograph shows a sample specimen that represents an actual laser production weld of the .0215” Ø Ni wire into the Ni lead adapter.

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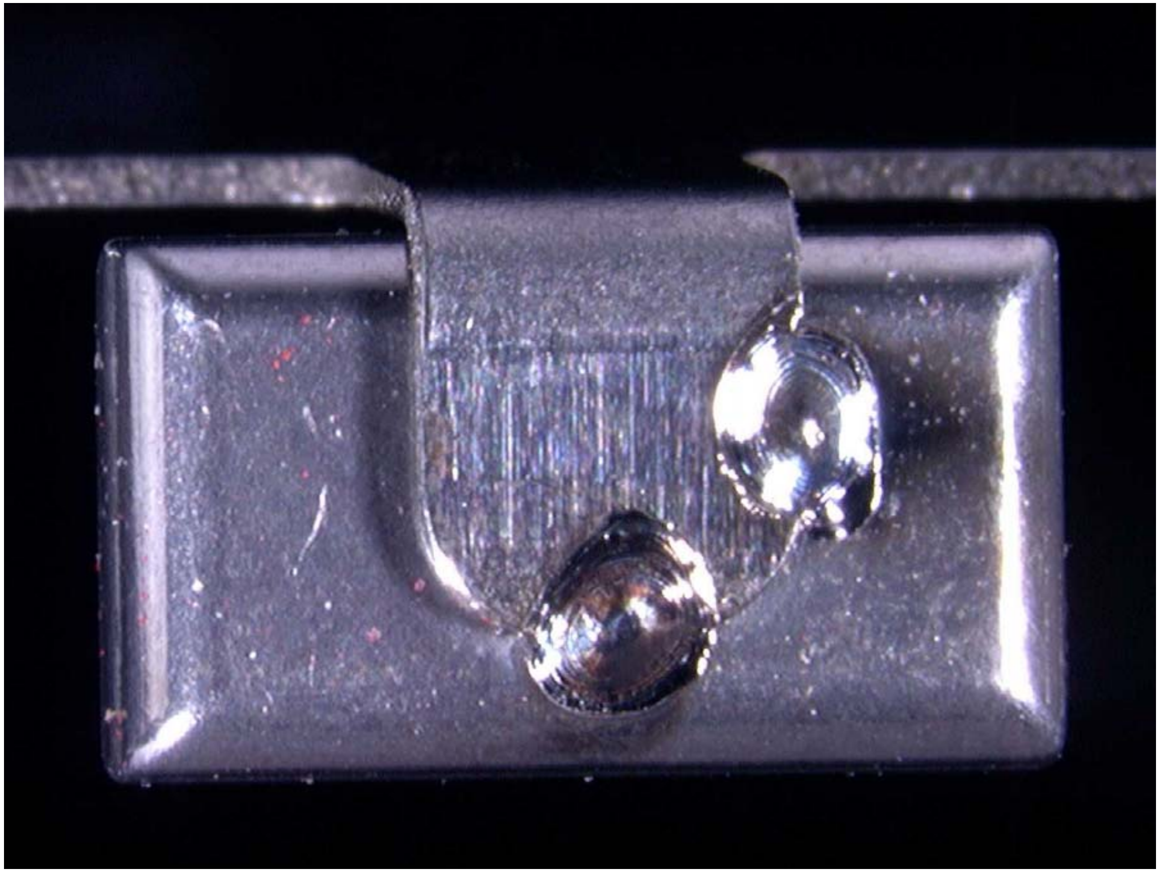
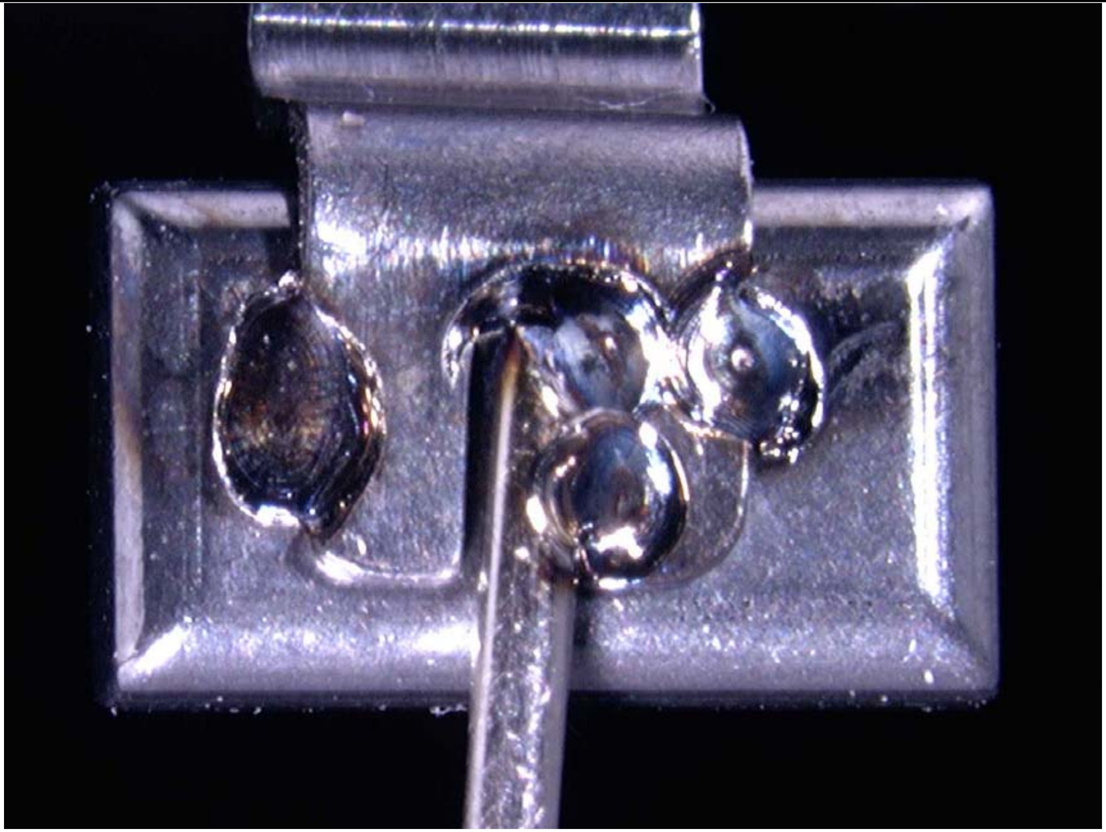
Metallurgical Evaluations



This photograph shows a sample specimen that represents an actual laser production lap weld of the .010" Kovar sheet to the Kovar flat tab.

MC4368A/MC4531 Laser Welding
Metallurgical Evaluations



This photograph shows a sample specimen that represents three types of actual laser production welds: (1) the .010” Kovar sheet to the flat tab, (2) the .0215” Ø Ni wire to the .010” Kovar sheet & (3) the rounding of the end of the .0215” Ø Ni wire.